Utilization of Potential Method for Measurement of Kinetics of Crack Growth Rate for Materials in Power Engineering

Využití potenciálové metody měření kinetiky růstu trhlin pro materiály v energetice

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The paper summarizes results of experimental work carried out within the project TH02020071 „Research of the method of potential measuring system for monitoring initiation, stable and unstable crack growth for new industry applications". The paper and project deal with the study of possibilities of the method of potential measuring system for measurement of crack growth rate and initiation of stable crack growth of metallic materials in high-pressure hydrogen environment, where the application of other measuring method is difficult. The main goal of this project is research and development of the method of potential measuring system that can be used for measurement of crack growth rate of fatigue cracks in high-pressure hydrogen environment and for initiation and growth measurement of creep cracks in operating power plants. Use of the measuring system will be extended to a new area of material testing and for new industry application, where creep and fatigue crack growth influencing the service life should be taken into account. Other aims of the above-mentioned project are proposal and certification of the new methodologies for measurement of crack growth rate of the fatigue cracks for special industry application, initiation, and growth of the creep cracks and evaluation of the fracture toughness of the structural steels and welds in a high-pressure environment. Theoretical background of potential methods is presented in the introductory comparison of recent methods, including the proposal of placement of electrodes that used in engineering practice. After theoretical review description of experimental works is presented, including results of measurement of crack growth rate in structural steels used for manufacturing of cylinders. The results obtained show relative high resistance against hydrogen embrittlement of the investigated steel as well as a change in fracture mechanisms in fracture surfaces in hydrogen compared to the air. All the results were obtained in newly developed High-pressure hydrogen autoclave that was built in our company.

***Key words**: potential method; crack growth rate; fracture toughness; high-pressure hydrogen environment*

Článek shrnuje výsledky prací provedených při řešení projektu TH02020071 Výzkum měřícího systému potenciálové metody pro sledování iniciace, stabilního a nestabilního růstu trhlin pro nové průmyslové aplikace. Článek a projekt se zabývá studiem možností aplikace měřícího systému potenciálové metody pro měření kinetiky růstu trhlin a lomové houževnatosti kovových materiálů v prostředí vysokotlakého vodíku, kde je použití jiných měřících metod pro sledování růstu únavových trhlin obtížné. Využití potenciometrické metody v průmyslové praxi pro měření délek trhlin je poměrně malé. Pro širší nasazení v průmyslu doposud schází dostatek relevantních dat, geometrických kalibrací a dalších konkrétních parametrů pro optimální nastavení citlivosti snímání signálu, které se případ od případu liší. Článek sumarizuje doposud získané výsledky při řešení projektu.

***Klíčová slova**: potenciálová metoda; kinetika růstu trhlin; lomová houževnatost; prostředí vysokotlakého vodíku*

At present, the use of the potential method in the industrial practice for measuring crack lengths is relatively small. Although numerous industrial applications exist, for which the potential method of tracking the growth of sub-critical defects would undoubtedly be a good choice, there is still a lack of relevant data, geometric calibrations, and other concrete parameters for an optimal setting of the sensitivity of the signal reading, which differ from case to case. The lack of calibration curves for individual types of materials is also limiting. For practical industrial applications, such as measuring the growth of creep cracks in the power engineering, or measurement of the growth of cracks in enclosed pressure systems with different environments (hydrogen, water, steam, etc.), different measuring systems are still in use, but they do not enable a measurement of crack growth in situ. The article summarizes the theoretical aspects of measurement by the potential method and it summarizes also the evaluation of some initial experiments. Application of high pressure hydrogen cylinders was chosen for the first series of experimental works.

Hutnické listy č. 4/2017, roč. LXX
ISSN 0018-8069

Principle of potential method

Methods using alternating potentials are methods that have been developed and proven for many decades and used for measuring surface defects, cracks, for evaluation of material properties (conductivity, permeability) and for determination of material of the sample. The main advantages of these methods include low measuring current, the smaller size of the instrument, relatively distinct measured signals, theoretically higher sensitivity to surface defects, a linear dependence of the crack length on the measured signal. The disadvantages include, in particular, rather difficult measurement of ferromagnetic materials and influencing of the measurement by the power supply conductors.

The basic principle of the method using alternating potentials, as well as of all other potential methods, is the introduction of electrical current into the investigated material and the measurement of the generated electric field. In the case of the known conductivity of the material, it is then possible to assess the presence of defects or cracks. The measurement is most often performed by a four-point method using a probe or by welding of the measuring electrodes to the material sample by spot welding (Fig. 1). The outer electrodes serve for introduction of an alternating current and for the creation of an electric field. The inner electrodes detect the difference of potentials on the material surface.

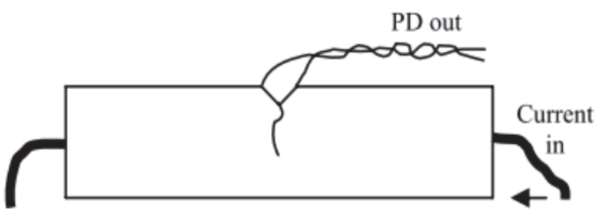

Fig. 1 Schematic diagram of the 4-point connection of electrodes for potential method [1]

Obr. 1 Schématické znázornění čtyřbodového připojení elektrod pro potenciálovou metodu [1]

The principal difference between the methods of alternating current potential drop (ACPD) and direct current potential drop (DCPD) consists in the fact that alternate methods use the skin effect described above for determination of the depth of penetration of electric field and thus for determination of the effective cross-section through which the electric current runs. Properties of the skin effect are advantageously used for measurement with the use of relatively low currents, which can produce a sufficiently large potential difference over a small cross-section without affecting the measurement by heating of material and for an increase in sensitivity to the surface defects (Fig. 2). Another advantage of the skin effect is the linear dependence between the crack size and the change in the specific resistance of the material, which can be determined, for example, by a reference measurements at the place without defects. If the probe is situated above the material defect, the distance from the probe to the defect, which the current must overcome, is extended, which causes a greater difference in potentials of the measuring electrodes as shown in Fig. 2 [2, 3]. The measurement frequencies of alternate potential methods fluctuate commonly in the order of tens of kHz. When selecting lower frequencies, a greater depth of penetration of the generated electric field is achieved, and thus also the possibility of detecting subsurface defects. At the same time, the sensitivity to surface defects decreases.

Thanks to the long time development and high sensitivity of the methods based on eddy currents, numerous possible applications were discovered, such as measuring the sample thickness, measuring of the distance between the sample and the coil, measuring of thickness of non-conductive material on a conductive sample, detection of cracks and unevenness, and changes in conductivity and permeability.

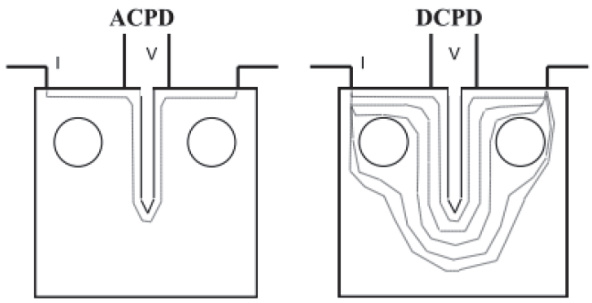

Fig. 2 Paths of current running through the crack with the use of AC potential method (left) and DC potential method (right) [2]

Obr. 2 Cesty protékajícího proudu přes trhlinu střídavou (vlevo) potenciálovou metodou a stejnosměrnou potenciálovou metodou (vpravo) [2]

Direct current potential drop methods belong to the oldest, most accurate and most widely used methods of nondestructive testing for detection of initiation, tracking of growth, and measurement of crack geometry in both laboratory and industrial tests. In addition to their simplicity and the possibility of complete automation, they have a number of advantages over other electromagnetic methods of nondestructive testing. The independence of DCPD methods on the material permeability makes it possible to measure accurately also ferromagnetic materials where both ACPD methods and methods based on eddy current fail. Other advantages include a simpler design of the direct current source, lower susceptibility to induced noise in the conductors. On the contrary, the problems related to those methods include the namely use of high currents and related possibility of heating of the sample, nonlinear calibration, and errors caused by thermoelectric voltages.

The basic principle of DCPD methods is, similarly in the case of ADPD methods, the measurement of voltage on the surface of the sample, through which passes electric current and the calculation of the specific resistance of the material. The measurement is most often performed by a four-point method, where the two outer electrodes serve to introduce the current into the measured sample and the inner electrodes serve to measure the difference of potential of the crack. The electrodes can be spot welded onto the sample (Fig. 1) or they can be applied by a measuring probe. With the extended length of the crack, the resistance of the material increases since the cross-section of the sample decreases, and the difference in potentials on the measuring electrodes increases. Crack parameters can be evaluated in the following manner:

1) on the basis of experimentally obtained calibration curves; this is the most commonly used method; the disadvantage is the necessity of calibration against another measuring device,
2) by the finite element method,
3) analytically – only for simple geometries.

In comparison to the ACPD methods the DCPD methods are characterized by significantly higher currents in the order of tens of A. In order to avoid an excessive and undesirable heating of the sample, pulse measurement is usedd. In the pulse mode, the current is introduced into the material only for the time necessary for one measurement followed by a relatively long gap before the next measurement. In the case of material tests, it is suitable to ensure synchronization with the testing (loading) equipment in order to start the measurement precisely within the load cycle when the crack is open (Fig. 3). [1]

The layout of the electrodes shown in Fig. 2 is appropriate particularly for observation of the initiation and growth of cracks in material samples.

The DCPD methods are well suited for the detection and analysis of cracks on the reverse side of the investigated material. Unlike ACPD methods, the depth of penetration of the generated electric field does not depend on the material permeability. This can be, in dependence also on the geometry of the used measuring probe, created even deep in the material. Since the density of the electric current considerably decreases with the depth, the voltage drops in comparison with the same surface crack are also smaller – see Fig. 4. Particularly in thick-walled materials, it is necessary to apply considerable measurement currents for the achievement of the required sensitivity, which, on the other hand, with use of the measuring probes can produce noise caused by transition resistances at the point of contact.

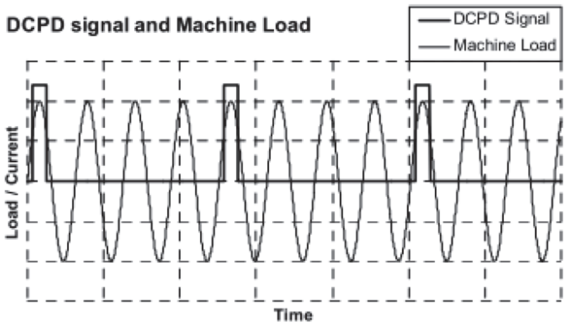

Fig. 3 Pulse DCPD method synchronized with the load cycle [1]
Obr. 3 Pulzní stejnosměrná metoda synchronizovaná se zatěžovacím cyklem [1]

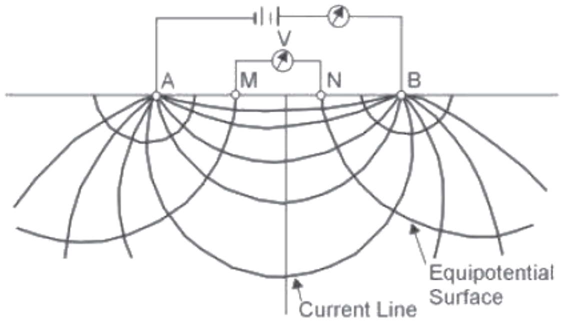

Fig. 4 Visualisation of current and equipotential lines in spatial electric field [4]
Obr. 4 Vizualizace proudových a ekvipotenciálových čar v prostorovém elektrickém poli [4]

The DCPD methods are susceptible to errors associated with the generation of thermoelectric stresses on the signal electrodes. Under ideal conditions where the sample material and the electrodes are completely homogeneous and the temperature in the measurement area is locally and temporally constant, the thermoelectric voltages are automatically read. In practice, however, the materials are non-homogeneous, the environment temperature may fluctuate over time and may not be the same in all places (temperature gradients). The solution to the problem is to a certain extent the use of the so-called quasi-DC mode when first the measurement of the difference of potentials is made with the introduced measuring current, burdened by errors from the thermoelectric voltages and immediately afterwards a measurement is performed with a zero measuring current, which measures purely the thermoelectric voltages. Error correction is made by simple subtraction of these two values. The measurement in an environment with rapid temperature changes still presents a problem. The double time of measurement, which can last even several seconds depending on the thickness and permeability of the material, is another disadvantage. The DCPD methods are used for detection of both internal and external cracks, for tracking of initiation and growth of cracks, for recognition of materials including alloys, for measurement of thickness, for measurement of conductivity (including also the poorly conductive materials such as semiconductors), for measurement of soil properties (density, porosity, resistivity), for their identification and for creation of sub surface 2D and 3D profiles. The potential method modified by Ing. Korec, CSc. [5] from Techlab, s.r.o., is essentially a combination of the advantages of the above-mentioned AC and DC potential drop methods. It finds its application mainly in the detection and measurement of the geometry of cracks, in the monitoring of corrosion, in the measurement of thickness and of plastic deformation on steam and other pipelines and of material samples during loading tests. It took over the positive features of the DCPD methods, such as the ability to measure also the materials that cannot be measured by the ACPD methods, good repeatability, the ability to measure deep defects and cracks on the inner sides of the pipe and independence on the position of the power supply conductors. Positive properties of the ACPD methods comprise namely use of a low measuring current (typically 1A), which allows the use of lighter power supply conductors, continuous measurements without the risk of overheating, battery operation and associated improved mobility of the instrument. The method uses different properties of geometrically different potential fields formed around the current electrodes. The courses of electric potential $U(x)$ in dependence on the distance x from the current electrode, are the following [5]:

1) Linear – the field is deformed by the final diameter of the material. It is created, for example, in test rods or pipes of small diameters. The dependence of the electrical potential on the distances from the current electrode in the linear electric field can be expressed by the following relation:

$$U(x) = I_M \cdot \frac{\rho}{S} \cdot x\,, \tag{1}$$

where I_M is the measuring current, ρ is the material specific electrical resistance, S is material cross-section an x is the distance from the power supply electrode.

2) Planar – the field is deformed by the final thickness of the material. It is created, for example, in the vessel shells and in pipes of larger diameter. The dependence of the electrical potential on the distance from the current electrode in the planar electric field can be expressed by the following relation:

$$U(x) = I_M \cdot \frac{\rho}{t} \cdot (-\ln x)\,, \tag{2}$$

where t is material thickness.

3) Spatial – the field is not affected by the final dimensions of the material. It is created mainly in thick-walled vessels and pipelines. The dependence of the electrical potential on the distance from the current electrode in the spatial electric field can be expressed by the following relation:

$$U(x) = I_M \cdot \rho \cdot \frac{1}{x}\,, \tag{3}$$

Parameters in the equation (3) are the same as in the previous equations (1) and (2).

Characteristic courses of potential between two electrodes are formed by superposition of the fields of the positive and negative electrode. The shape of the electric field depends on the geometry of the investigated sample and on the choice of the distances of the current electrodes. For the spatial electric field, the distance between the current electrodes ***a*** must be less than the thickness of the material ***t*** [5]. For the planar electric field, the distance between the current electrodes *a* must be greater than three times the thickness of the material ***t***. [5]

The measurement is most often arranged as a *pair of four-electrode systems*, where the outer electrodes of each system serve for the introduction of the measuring current and the inner electrodes serve for measuring the difference of potentials. Both systems are located in the same place, but with different spacing so that one forms a spatial electric field serving for the measurement of the specific resistance of the material, and the other forms a flat electric field used for measurement of the thickness. The advantage of this arrangement is the independence of results on the actual temperature or on the accuracy of the measuring current. It finds its use mainly in the measurement of thicknesses and plastic deformations in steam and other pipelines [6].

Other possible configurations include a *four-electrode* system, used for measurement of crack propagation rate, especially in fatigue tests. The electrodes are situated symmetrically around the crack. The test current flows through the test sample and the difference of potentials is measured at the point of the crack. Assuming that the current is evenly distributed in the sample and that the crack size is much smaller than the sample width, it is possible to evaluate the rate of crack propagation [6].

Another possible arrangement is a *six-electrode* arrangement, which is analogous to the previous one. It serves for measurement of the geometry of the known cracks. The pair of electrodes serves for the introduction of the I_M current into the material sample. The other two pairs are symmetrically positioned over the crack but with different spacings y. On the basis of the measured differences of potentials, it is possible to evaluate the crack length. This arrangement is characterized by very good long-term stability and by suppression of the influence of material properties and temperature fluctuations on the measurement accuracy.

The *four-electrode arrangement* of the potential method in the form of a hand-held probe can be used for detection of both external and internal cracks. The evaluation is based on the relation of the individual measurements from the area of interest to the reference measurement carried out on a near location without defects, or on the same material without defects at the same temperature.

Experimental methods, results of measurements

The connection of the electrodes at the measurement of the crack growth on test specimens 1/2CT was tuned and practically tested at the measurement of the resistance of the material of the pressure cylinders to the corrosive action of high-pressure hydrogen. As a test material, the steel 34CrNiMo6 designated for production of hydrogen storage cylinders was chosen as a test material.

The test results according to the valid ISO 11114-4 [7] in high-pressure hydrogen under pressure of 15 MPa are presented in Tab. 1. The load on the test specimens was calculated on the basis of numerical simulation (Fig. 5) and it was set to $P_{max} = 346$ MPa [8], to which corresponded the maximum value of the stress intensity factor $K_{max} = 27$ MPa·m$^{1/2}$. The coefficient of asymmetry of the cycle R was determined with respect to practical applications in industrial practice to be $R = 0.63$. The range of the stress intensity factor was calculated to be $\Delta K = 9.5$ MPa·m$^{1/2}$. The testing frequency in the environment of pressurized hydrogen was 7 Hz.

Tab. 1 Results of the test of 34CrNiMo6 steel
Tab. 1 Výsledky zkoušek materiálu 34CrNiMo6

Specimen ID	Crack length at the start	Crack length at the end	Number of cycles	Note
	a_0	a_t	N	
	(mm)		(-)	
L8	10.96	10.96	50,000	not failed
	10.83	10.83		
L9	11.10	11.10	50,000	not failed
	11.15	11.15		
L10	11.13	11.13	50,000	not failed
	11.20	11.20		
L11	11.30	11.52	150,000	not failed
	11.30	11.47		
L13	11.25	11.38	150,000	not failed
	11.55	11.76		
L14	11.10	11.29	150,000	not failed
	11.10	11.22		

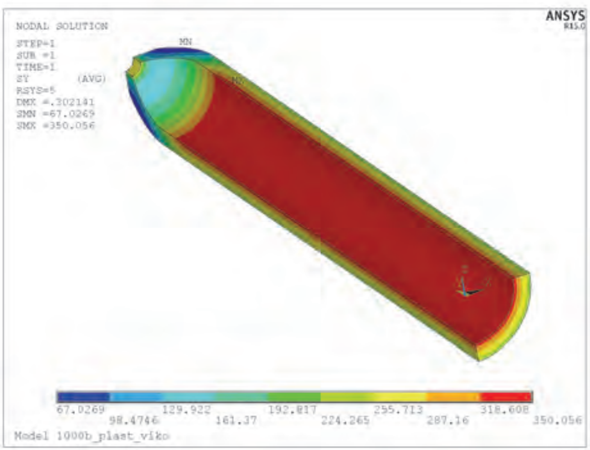

Fig. 5 Numeric simulation of evolution of stresses in the pressure cylinder [8]
Obr. 5 Numerická simulace průběhu napětí v tlakové láhvi [8]

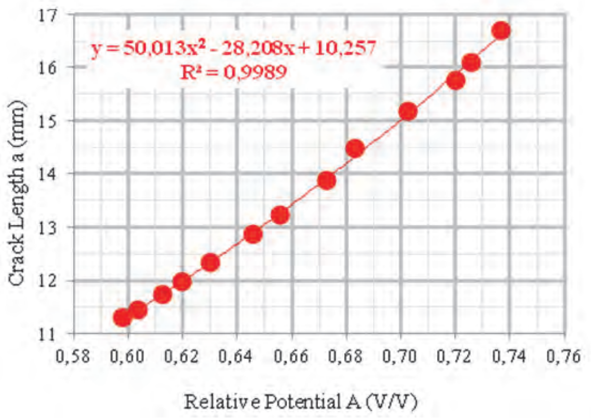

Fig. 6 Calibration curve of the ACPD method for CT specimen [9]
Obr. 6 Kalibrační křivka ACPD metody pro CT vzorek [9]

Tab. 2 Results of measurement of crack growth rate in high-pressure hydrogen environment
Tab. 2 Výsledky měření kinetiky růstu trhliny v prostředí vysokotla-kého vodíku pro definovaný růst trhliny

Spec.	Average crack length at the start	Average crack length at the end	Number of cycles	Note
	a_0	a_t	N	
	(mm)		(-)	
L16	11.48	12.98	192,528	not failed

Table 2 shows the result of measurement of the kinetics of the fatigue crack growth in the phase of sub-critical growth when the maximal length of the defect of 1.5 mm is considered to be the limit value of permissible indication in the pressure cylinder. The testing was performed with the same parameters as in the case of results shown in Tab. 1. The crack length measurement was performed by a potential method on the basis of the calibration curve shown in Fig. 6. It is evident from Tab. 2 that for the given material, cycle asymmetry and high-pressure hydrogen environment, the number of cycles necessary for reaching the maximal permissible defect size is given by approx. 200,000 cycles. No unstable propagation took place reaching the permissible defect size.

Figures 7 to 9 show a fractographic analysis of the fracture area of the sample L16. Fig. 7 shows the visible difference between the areas of pre-cycling in the air and the actual measurement of the crack growth kinetics in the high-pressure cylinder. Details of fractographic characteristics and differences are shown in Figs. 8 and 9.

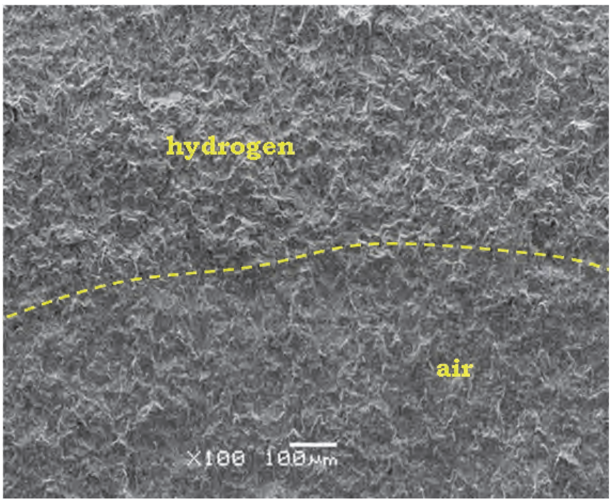

Fig. 7 Fracture surface, transition between pre-cycling area (air) and measurement of the crack growth kinetics (hydrogen)
Obr. 7 Lomová plocha, přechod mezi oblastí předcyklování (vzduch) a vlastního měření kinetiky růstu (vodík)

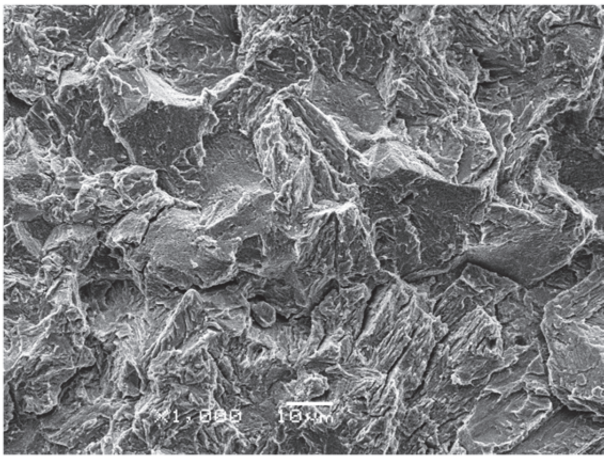

Fig. 8 Detail of pre-cycling area (air)
Obr. 8 Detail oblasti předcyklování (vzduch)

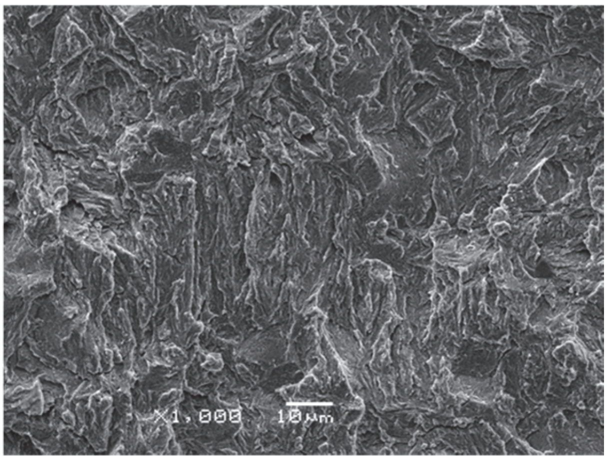

Fig. 9 Detail of the area of measurement of crack growth rate kinetics (hydrogen)
Obr. 9 Detail oblasti měření kinetiky růstu (vodík)

Conclusions

The paper deals with the study of possibilities of using the potential method for measuring the kinetics of crack growth in the CT test specimens. The paper presents a theoretical summary of aspects and possibilities of various configurations of the potential method. Parameter optimisation for individual geometries of test specimens results in significantly higher sensitivity. Wider use of this method was hitherto has been prevented by lack of knowledge of calibration curves for individual geometries of test specimens and for individual materials. This issue is addressed by the project TH02020071, which will continue until 2020. The direct practical realization output is the realised measurement of the kinetics of the fatigue crack growth in the test specimen ½ CT in a high-pressure hydrogen environment where another method for measurement of the crack growth rate in situ is not possible.

The conducted measurements show the high sensitivity of the potential method, as well as the fact that the evaluated material for the production of the pressure cylinders shows a very good resistance to degradation caused by high-pressure hydrogen.

It follows from realised fractographic analysis that the degradation effect of high-pressure hydrogen changes the character of the fracture surface, although the rate of crack growth in the selected cycle asymmetry corresponding to real operation is very low.

Acknowledgements

This work was created within a solution of the project ´TH02020071 Research of the Potential Method Measurement System for the Monitoring of Initiation, Stable and Unstable Crack Growth for New Industrial Applications´ funded by the Technology Agency of the Czech Republic.

Literature

[1] CLÁUDIO, R. A., MAIA, V., DIAS PEREIRA, J. M., BAPTISTA, R., BRANCO, C. M., BYRNE, J. Development of a DC Potential Drop System Controlled by Computer. In 9th *Portuguese Conference on Fracture*. 2004.

[2] SPOSITO, G. *Advances in Potential Drop Techniques for Non-destructive Testing*. London: Imperial College. 2009.

[3] SPOSITO, G. CAWLEY, P., NAGY, P. B. An approximate model for three-dimensional alternating current potential drop analyses using a commercial finite element code. NDT&E International. 43 (2009), 134–140, ISSN 0963-8695.

[4] *Resistivity Methods. Environmental Geophysics*. [Online] U.S. Environmental protection agency, Graz University of Technology, 2011. [Cit. 06. 04. 2014] http://www.epa.gov/esd/cmb/GeophysicsWebsite/pages/reference/methods/Surface_Geophysical_Methods/Electrical_Methods/Resistivity_Methods.htm

[5] KOREC, L. *Měření deformace při tečení materiálu potenciálovou metodou [Measurement of deformation at material creep by potential method]*. Praha: Techlab, 2014.

[6] KOREC, L. *Odečítací jednotka pro měření potenciálovou metodou Techlab SRT-4K [Reading unit for measurement by potential method Techlab SRT-4K]*. Praha: Techlab, 2007.

[7] *ISO 11114-4: 2005* Transportable Gas Cylinders – Compatibility of Cylinder and Valve Materials with Gas Contents – Part 4: The Test Methods for Selecting Metallic Material Resistant to Hydrogen Embrittlement.

[8] PŘICHYSTAL, I. Analýza bezešvých tlakových nádob na uskladnění vodíku – stanovení velikosti obvodového napětí ve válcové části [Analysis of seamless pressure vessels for hydrogen storage - determination of the size of hoop stress in the cylindrical part]. Report V3141/15, Ostrava: VITKOVICE-UAM, July 2015, Brno.

[9] KANDER, L., STEJSKALOVÁ, Š., ČÍŽEK, P. Effect of High Pressure Hydrogen Environment on Fatigue Crack Growth Rate Properties of Structural Steel Used for Cylinders. In *METAL 2017*, will be published

Strojírna ArcelorMittal v Ostravě vyrobí nápravy pro tramvaje na fotbalové mistrovství světa v Rusku v roce 2018

Tramvaje, které budou příští rok přepravovat fanoušky i hráče na fotbalovém mistrovství světa ve fotbale 2018 v Rusku, v sobě ponesou ocel z Ostravy. Strojírna ArcelorMittal Engineering Products Ostrava, dceřiná společnost huti ArcelorMittal Ostrava, získala zakázku na výrobu téměř 1000 náprav pro nový typ tramvají.

„Ve výrobě tramvajových náprav máme už více než šedesát let zkušeností. Výrobu všech náprav pro nový typ tramvaje, který se bude používat na fotbalovém mistrovství světa 2018, dokončíme letos v listopadu, aby se vše stihlo včas dodat a zkompletovat," říká Daniel Doležal, manažer pro prodej a marketing ArcelorMittal Engineering Products Ostrava.

Nápravy jsou určeny pro nový typ moderních tramvají 71-931M "Vityaz-M", které budou během fotbalového šampionátu přepravovat fanoušky i hráče. Jedná se o vylepšenou verzi tramvaje 71-931 "Vityaz", která je zcela nízkopodlažní a pojme až 265 cestujících. Nápravy vyrobené ostravskou strojírnou ArcelorMittal budou použity pro přibližně 150 tramvají.

Strojírna ArcelorMittal Engineering Products Ostrava dodává tramvajové nápravy především svým tuzemským partnerům. Hotové tramvaje pak kromě tuzemska putují na Slovensko, do Maďarska, Francie, Turecka, Ruska a na Ukrajinu.

- *z tiskové zprávy* **-**

Inovace oceli určují budoucnost

Stahl und Eisen *4/2017*

Na 21. výročním jednání deníku Handelsblatt „Ocelářský trh 2017" v únoru v Düsseldorfu byly kromě témat a diskusních okruhů k aktuální strukturální a politickohospodářské situaci ocelářského průmyslu představeny také inovativní řešení s ocelí. Přednáškový blok prezentoval aktuální projekty a inovace týkající se vysoce výkonného materiálu ocel. Německo disponuje jedinečnou výzkumnou sítí, zabývající se ocelí, která zahrnuje univerzitní, mimouniverzitní a průmyslový vývoj a výzkum. Výzkumná síť ocelářského výzkumu sahá od dobývání rudy až k užitnému produktu a zapojeny jsou všechny články řetězce tvorby hodnot. Výzkumná agenda má tři těžiště: technologie k omezování a využívání CO_2, optimalizace procesních řetězců (strategie nulových chyb, průmysl 4.0) a přidaná hodnota díky používání oceli. V Evropě se dnes vyrábí kolem 2500 normovaných ocelí. Každý rok je ca 150 ocelí v jejich vlastnostech vylepšeno a nově vyvinuto. Výkonnost oceli se dobře ukazuje na těchto čtyřech příkladech: a) karoserie z vysokopevných ocelí zachycují v průběhu několika milisekund výraznou pohybovou energii, a optimálně chrání cestující ve vozidle. Strukturní prvky z inovativních ocelí mají až o 30 % vyšší schopnost přijímat energii a to při snížené deformaci, b) písty pro dieselové motory osobních aut z vysokopevných zušlechtěných ocelí mají díky vyšší mechanické a tepelné zatížitelnosti až o 30 % menší konstrukční výšku než hliníkové písty. Ocelové písty poskytují podstatný příspěvek k plnění stále náročnějších předpisů k emisím CO_2, c) potravinářské plechovky jsou vyráběny z ultratenkého bílého plechu o tloušťce 0,13 mm. Při stejném plnicím množství je tak plechovka o polovinu tenčí a těžká. Recyklační kvóta je s 90 % největší na světě, d) oba vnitřní podvozky Airbusu A380 vydrží díky použití vysokopevných zušlechtěných ocelí zátěž 520 tun při přistání. To odpovídá váze 400 aut VW Golf.