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Characterization of Cracking Behaviour for Steel Used in Steam-Line Pipes Manufacture

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Abstract

The main objective of this paper was to characterize the cracking behaviour of power-plant steel, after working for 44 thousand hours. The cracking resistance, on compact samples, was determined. The critical cracking force was established basing on the signal from the strain gauge applied in crack vicinity. Based on the impact tests, the resiliency is determined. Microhardness Vickers tests were conducted in the vicinity of the crack, on compact samples loaded at the same force level, but with different pre-cracks lengths. A study was also made on the differences between the hardness values for the case of static loading, behind the elasticity limit, and, respectively, for the case of impact loading.

Keywords: *microhardness, cracking behaviour, plastic deformation.*

Introduction

Some samples of X20CrMoV121 were the subject for the present study. The steel was used for manufacturing some steam-line pipes that functioned, for approx. 44000 hours, at high temperature and pressure parameters: p=130daN/cm^2 and T=530°C. In order to determine the security of a future exploitation of the steel, a characterization of cracking behaviour was proposed.

In this work, some tests on compact samples, as well as impact tests were conducted. One can assume that the design procedures that were used insure the integrity of a component through the operational life, postulating that the component has a continuous and compact structure, without any flaws. Nevertheless, a certain component may contain pre-existing flaws, like structural inhomogeneities, which are preferential local sites for the initiation of voids and micro-cracks. During the operational history, these structural inhomogeneities may grow and coalesce and may finally lead to unexpected rupture or failure of the component. Therefore, failure analyses become more acceptable for the estimation of the allowable operational life.

In most cases, the initiation of a crack in a structural flaw is introduced by repeated operational load (fatigue or thermal fatigue); the corresponding developed crack may additionally grow slowly under steady-state loadings (creep crack growth). By the

growth and/or coalescence of micro-cracks, a critical defect size may result, which may lead to a spontaneous (catastrophic) failure of the respective component. Therefore, information on crack growth behaviour under all kind of loading conditions is needed, in order to estimate the long term structural strength of the component.

At this aim, the knowledge of high temperature fracture mechanical properties is required, for the studied material [1]. This requirement can be satisfied by experimental work, on fracture mechanics specimens from the alloy exposed at high working temperatures, under thermal fatigue, steady sate (creep) loads and/or under combined loading cycles in working fluids.

The X20CrMoV121 steel provides the highest creep resistance at temperature of about 600^0C. For temperature above 550^0C, the questions concerning steam oxidation resistance is still under consideration. It is important to note that very limited reported results are available, concerning the crack growth behaviour of that steel.

Material and experimental details

The failure mode is a function of material properties, rate of loading, temperature and component thickness. The high-chromium steels were developed, during the second half of 20^{th} century, as a substitute, of higher durability and weldability, for conventional austenitic steels. Initially, various types of high-strength steels were produced, containing 9% Cr (e.g. HCM9M, in Europe, or P9 in the U.S.). They showed, however, limited resistance to corrosion. Nowadays, a type of steel widely applied for components operating in high-temperature conditions is the X20CrMoV121, containing about 12% of chromium [2]. This is also the type of steel for samples that are investigated herein. They were cut out from some disaffected live-steam pipelines that operated into a local thermal power station. The steam lines had worked for 44 thousand hours at a maximum pressure level of 130 bar and at high temperature up to 530°C (the design parameters for that power installation were p = 151 bar and T = 555°C). The total number of cold-to-heat cycles was 193.

The composition of alloy steel was established from chemical analysis of samples, as follows: 0,19-0,21%C, 0,33-0,42%Si, 0,54-0,56%Mn, 0,018-0,019%P, 0,017-0,023%S, 0,47-0,49%Ni, 11,3-11,4%Cr, 0,93-0,94%Mo, 0,35%V (the balance of the composition is steel). These values are in good agreement with those that are indicated for the X20CrMoV121, by the corresponding material standards [5].

The compact tension (CT) specimen, as a component of the test method that is briefly described in this article, may be used to characterize the fracture behaviour of a certain material, by using the appropriate calculation techniques, irrespective of the failure mode. The compact tension specimen is, in some respects, similar to the SENB specimen, in that it is a proportional specimen of full plate thickness containing a fatigue crack. The specimen has a notch that is machined into one face, on the area to be tested, and a fatigue crack is then made, at the tip of the machined notch, to give a total 'crack' length approximately equivalent to the specimen thickness.

The specimen is tested in tension, and its deformation is measured by means of a clip gauge mounted across the mouth of the notch. Load and deformation are recorded and crack length is measured on the broken test piece. A decision could then be assumed, as to the failure mode and the appropriate analysis tools that are to be used, in order to determine the toughness of the studied material.

The compact tension test has the advantage, when compared with the SENB test, which the specimen is more economical in material consumption and that fact can be important when thick

plates are to be tested. The specimen is, however, more expensive in machining costs, and the method of loading tends to give lower toughness results than the SENB specimen. For that reason, the CT test is preferable to be applied by the power plant industry, where safety is crucial and lower bound results are preferred.

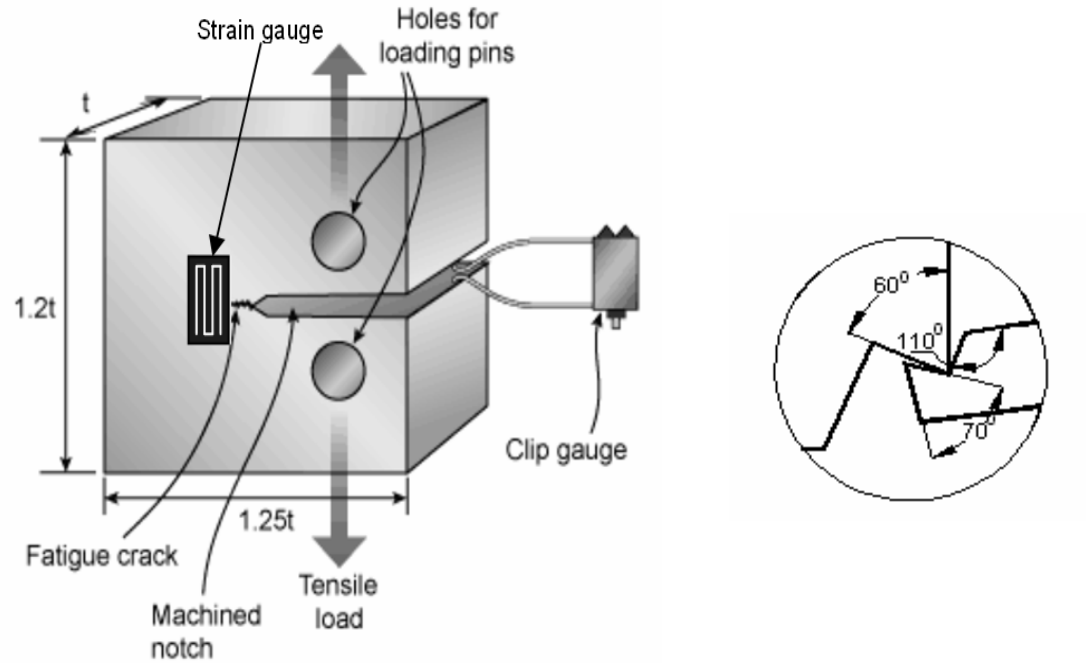


Fig.1. a) Compact tension specimen; b) Fixed mode of transducer [3].

For the present study, some compact tension specimens were manufactured on the width of the pipe wall, on different directions and with a notch, as presented in Fig. 1. All CT specimens were prepared according to the standard method prescriptions [6]. The notched CT-specimens were pre-cracked, at room temperature, by fatigue with a frequency of 85-90 Hz, in order to obtain a sharp crack tip. The length of cracks was measured using an ultrasonic apparatus for defect detection, so that the measurement errors were minimized. To determine the behaviour at impact breaking at ambient temperature, samples with U-shaped cuts and 5 mm depth were made, according to the standard specifications [7]. The loading scheme is presented in Fig. 2.

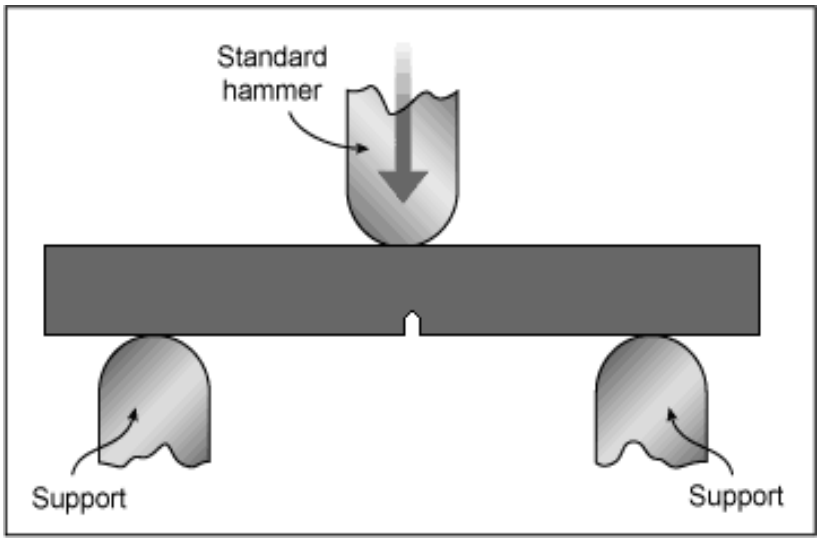


Fig. 2. Impact loading scheme.

Results and discussions

Determining fracture toughness

Fracture toughness is determined using the sample presenting an artificial crack, whose dimensions are superior to the flaws that are naturally existing in a material structure. The stress that is necessary to propagate that crack allows the calculation of fracture toughness K for the studied material. In order to achieve that aim, the compliance method is used, method that implies the determination of breaking energy.

The experimental determination of fracture toughness is standardized [6], and refers to samples from metallic materials having linear-elastic behaviour until breaking. The purpose of that test is to determine the critical value of the stress intensity factor K_{Ic}, in conditions of a plane strain state, together with the movement of the crack flanks. The method implies some standardized samples to be tested in tension; any sample has an initial lateral cut, in the presumed direction of crack propagation. During the test, more aspects are taken into consideration. The force-to-distance dependency, for the edges of the initial cut, should be drawn for any sample (Fig.3). The value for fracture toughness K is determined basing on calculation relationship that result from elastic stresses analysis [4], which is applied to the specific type of sample and loading.

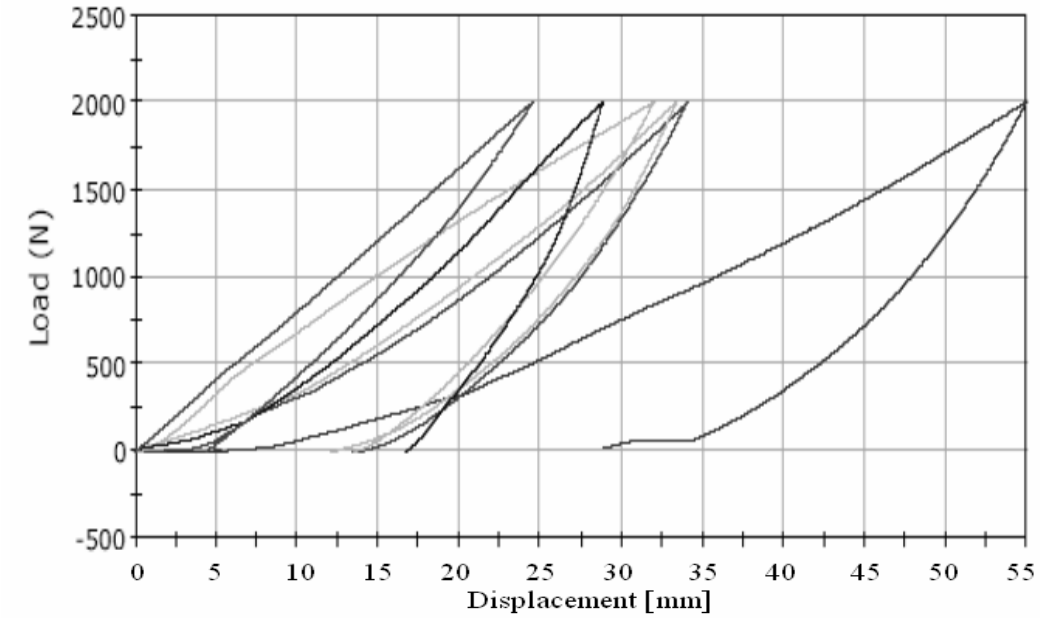


Fig. 3. Load-displacement dependences.

The samples were loaded on an INSTRON 3382 testing machine, which records the force-to-distance diagram. For an exact measurement of notch edges movement during the loading, a displacement transducer was installed on the sample, as presented in Fig. 1,b. The signal from the transducer was stored in the computer, using sampled recording, based on a National Instruments Data Acquisition System (Fig. 5). For the samples 1, ..*i*,...8 the corresponding lengths of their specific cracks, a_1, ...a_i...a_8. were measured. Each sample is characterized by a specific compliance, given by the relation $c = \frac{v}{F}$, in which v represents the movement of the application point for the F force.

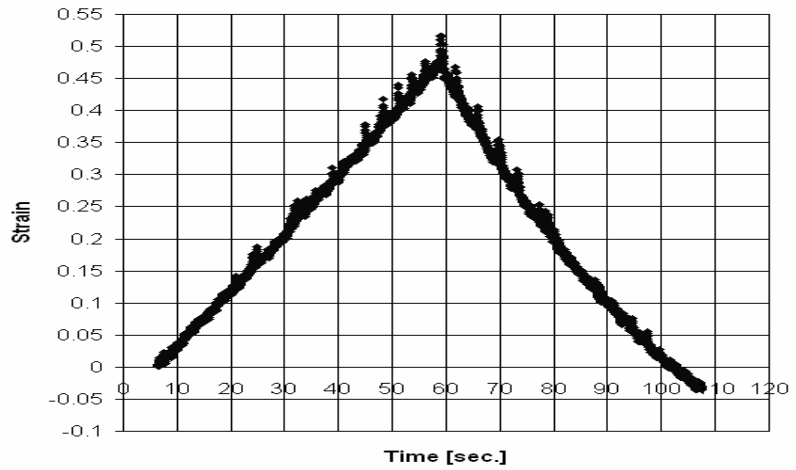


Fig. 5. The displacement values, as given by the "clip-on-gauge' transducer.

Each sample has $a_1,...a_i...a_8$ -length crack and they are loaded in tension, in the elastic deformation domain, so that the *F(v)* dependency is obtained. In order to minimize the measurements errors, that dependency was drawn using signals acquired through the data acquisition card, regarding the force and movement values.

For each sample with crack length a_i, the report $\frac{v}{F}$ gives the *C(a)* dependency (Fig. 6). For a sample with an intermediate crack length $a_1>a_i>a_n$ in which $a_1= a_i=a_5$=8,55 mm, $\left(\frac{\partial C}{\partial a}\right)_{a=a_i}$ is determined, as is graphically represented in Figure 6. The same sample is loaded in tension until it breaks and the critical force F, which led to its destruction, is obtained. The critical force was determined based on the signal acquired by the strain gauge installed on the sides of compact sample (Fig. 1,a), in the vicinity of crack propagated through fatigue.

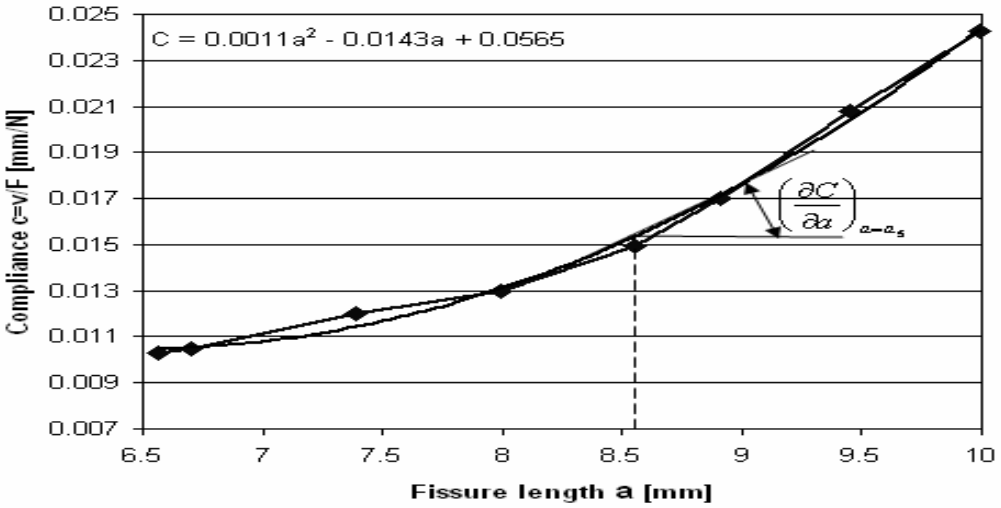


Fig. 6. Compliance- crack length dependence.

The calculus of tenacity at cracking, as a function of the compliance of the sample is given by the relation:

$$K_{Ic}^2 = \frac{E^* F_{cr}^2}{2t}\left(\frac{\partial C}{\partial a}\right)_{a=a_i} \tag{1}$$

in which: $E^* = \frac{E}{1-\upsilon^2}$ corresponds to the plane strain state; t is the sample depth, and F_{cr} represents the critical force at the moment of crack initiation.

When introducing the values obtained for $\left(\frac{\partial C}{\partial a}\right)_{a=a_i}$ and F_{cr} into the relation (2), the critical value K_{Ic} is obtained; it corresponds to the energy level that is required by the crack to propagate and transform into an unstable crack. This way, for $\left(\frac{\partial C}{\partial a}\right)_{a=a_i}$, the following relation can be established, based on the first derivate of the function that is presented in Figure 6:

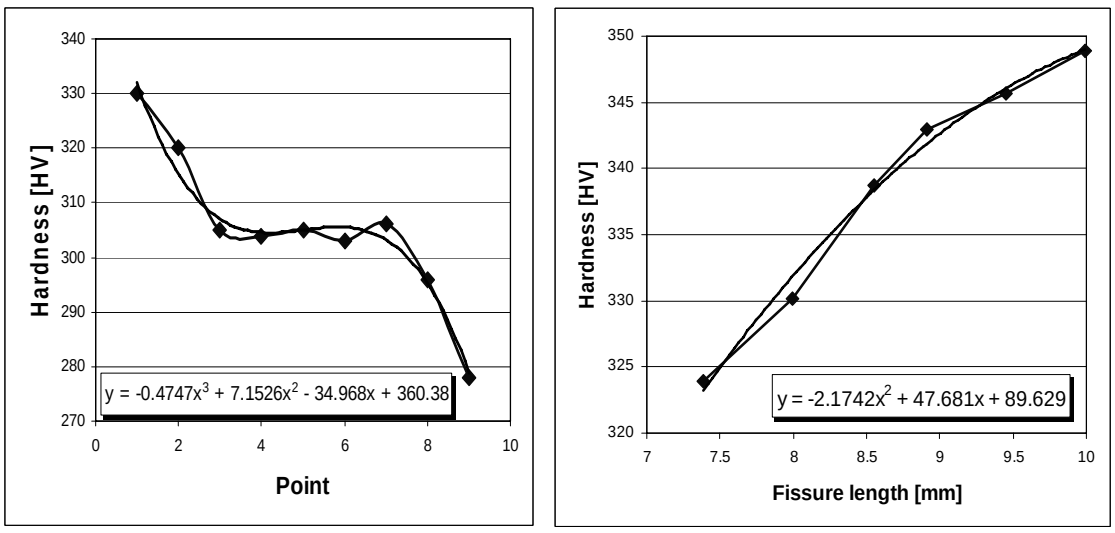
$$\left[\frac{\partial c}{\partial a}\right]_{a=8.55} = \left[2 \cdot 0.0011 \cdot a - 0.0143\right]_{a=8.55} = 0.00451 \tag{2}$$

Basing on the signal from the strain gauge that is installed on a sample loaded to break, it was established that the beginning of crack propagation was produced after t = 342 seconds. The testing speed was 0.5mm/s, so that the critical force corresponding to the initial moment of the crack propagation was F_{cr} = 3050N. With these data, the tenacity of crack will be as follows:

$$K_{Ic} = \sqrt{\frac{E^* F_{cr}^2}{2t}\left(\frac{\partial c}{\partial a}\right)_{a=a_5}} = 655.7 \ MPa\sqrt{m} \tag{3}$$

The hardness variation, as a function of crack length

On the compact samples with different (propagated through fatigue) crack lengths, previously loaded in tensile at a force level of 2000N, Vickers microhardness tests were conducted. A set of 7-9 indentations along the propagated crack was made. From the Figure 7,a (graph drawn for a sample), it can be concluded that, in the vicinity of crack, the hardness has a high value. This is possible because of the existence of a plastically deformed micro-zone.



a) *b)*

***Fig. 7**. a). The variation of hardness along the crack; b). The hardness variation as a function of crack length.*

One can assume that, in the zones with higher plastic deformation, the value of Vickers micro-hardness is also higher. The value of Vickers microhardness may be a measure of the plastic

deformation intensity – how far the material sample was loaded, beyond its elasticity limit. In a similar way, the microhardness values could indicate the existence of a crack in the vicinity of a local plastic micro-deformation.

As represented in Figure 7,b, the hardness variation was determined in one point nearby the crack, for 6 samples with different crack lengths. It was observed that the hardness values increased with the crack length. It happens because, while the crack length increases, the plastic deformation in vicinity of the crack tip is accentuated. As a consequence, one can assume that the value of Vickers microhardness is a measure of plastic micro-deformation state, in the vicinity of a crack.

Impact tests

Some impact tests, at ambient temperature and on standardized samples [7] were also conducted on the studied material. The notch of samples was U-shaped, with a depth of 5 mm. The impact energy levels for breaking the samples were situated between 38.21 J and 49.48 J, with an average value of 45.54 J. When analyzing the fracture surface, it was observed that a predominantly ductile behaviour could be ascertained to the studied steel. However, an important domain (approx. 35% of total area) was observed, at the center of breaking surfaces, whit a predominant brittle fracture aspect.

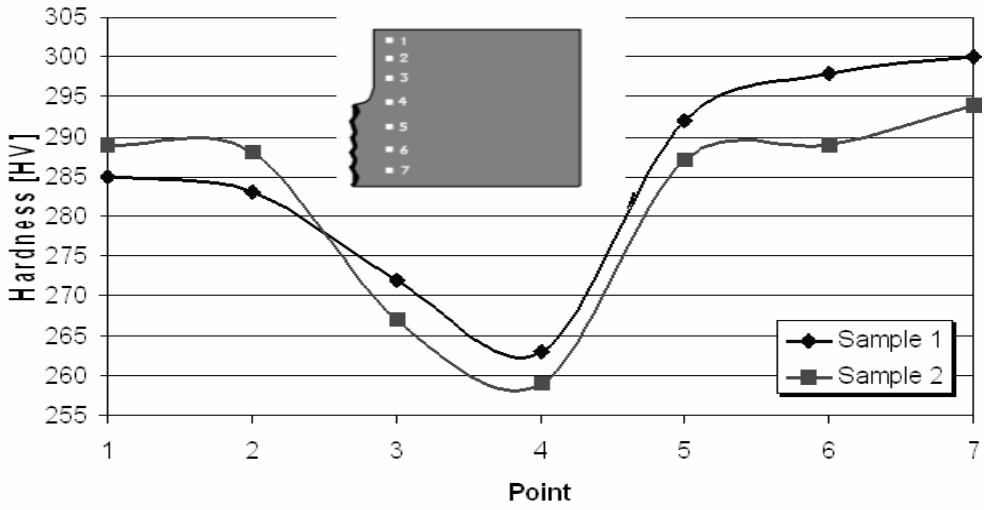


Fig. 8. Variation of Vickers micro hardness in the vicinity of impact-broken area

On the other hand, along the fracture surface (as a consequence of impact test), Vickers indentations were made (Fig. 8). It was observed, in the vicinity of the area where impact fracture was initiated, a substantial decrease of Vickers microhardness values occurs, while in the vicinity of the fracture surface those values are significantly increasing.

Conclusions

1. The value that was obtained for the fracture toughness of studied steel, using the compliance method, is similar to the values that are cited in literature.
2. Because of the local plastic deformation of the loaded crack-samples, Vickers microhardness increases when the measurement point it closer by the crack tip.
3. A significant Vickers microhardness variation was observed, in the vicinity of impact fracture surface.

References

1. Ennis P.J. - *Creep strengthening mechanism in the 9 to 12% chromium steels,* Advances in Material Technology for Fossil Power Plants (Proceed. Of Int. Conf.), p. 1146, 2004.
2. Hu Z.-F., Yang Z.-G. – *An investigation of the embrittlement in X20CrMoV121 power plant steel after long-term service exposure at elevated temperature*, Mat. Sci. & Eng., no. 93, pp. 224-229, 2004.
3. Matsumoto N., Nairn J.A. – *Fracture Toughness of MDF and other Materials with Fiber Bridging,* Proc. of 22nd Ann. Tech. Conf. of the Amer. Soc. of Composites, Seattle, WA, 2001.
4. Nairn, J. A. – *On the Calculation of Energy Release Rates for Cracked Laminates with Residual Stresses, Int. J. Fract. Mech*., 139, 267-293, 2006.
5. DIN 17175-79 – *Seamless Steel Tubes for Elevated Temperatures.*
6. ASTM Standard E399 – *Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials,* Annual Book of ASTM Standards, Vol. 03.01, 2005.
7. SR EN 10045:1993 – *Standard pentru încercarea la încovoiere prin şoc a materialelor metalice.*

Caracterizarea comportării la fisurare a unui oțel pentru conducte de abur viu

Rezumat

In cadrul acestei lucrări s-a realizat un studiu privind comportarea la fisurare a oțelului ***X20CrMoV121,*** *utilizat pentru conductele de abur viu de la termocentrale. S-a obținut tenacitatea la fisurare pe baza determinării variației complianței probei compacte in raport cu lungimea fisurii. In cadrul acestei determinari s-au utilizat semnalele de la mărcile tensometrice montate pe lateralele probei pentru determinarea momentului în care se inițiază propagarea fisurii. Pentru trasarea diagramelor F-v (forța-deplasarea flancurilor crestăturii) s-au utilizat semnalele de la maşina de încercat şi, respectiv, de la dispozitivul montat în acest sens pe probă.*

Pe probele compacte, solicitate anterior la aceeaşi forță, s-au efectuat microindentări Vickers în lungul fisurii propagate prin oboseală. Valorile obținute arată că duritatea creşte pe măsură ce punctul de măsurare se apropie de vârful fisurii.

Pe probe standardizate confectionate din acelaşi material s-au efectuat teste de încovoiere prin şoc la temperatura ambiantă. Aspectul suprafeței rupte demonstrează tenacitatea materialului. In acelasi timp, existența unei porțiuni cu rupere fragilă arată faptul că zona elastică s-a extins prin ecruisare, ducând la creşterea rezistenței materialului la presiunea şi temperatura prescrise.

Rezultate interesante s-au obținut şi prin analiza variației valorilor microdurității Vickers în puncte aflate pe o linie paralelă şi vecină cu suprafața de rupere a probelor încercate la şoc.