NON-INVASIVE METHODS FOR THE ESTIMATION OF CREEP PROPERTIES OF HEAT-RESISTANT STEELS

NEPORUŠNA METODA ZA DOLOČANJE LASTNOSTI TOPLOTNO OBSTOJNIH JEKEL PRI DEFORMACIJI Z LEZENJEM

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Residual life assessment of many components of power plants operating at high temperatures requires an accurate knowledge of the actual mechanical properties obtained without excessive interruption of the plant service. This can be achieved by a combination of miniaturized sampling (e.g., using SSAM apparatus) and relevant testing methods. The testing consists of the deformation of disk specimen with a shaped penetrator. Two principal testing methods can be applied with either constant rate of penetration (CRP) or constant force of penetration (CFP). For the further evaluation of the critical heat resistant properties, reliable relations between results of these tests and corresponding conventional tests performed on bulk specimens must be known. In the present paper some results of CFP tests obtained on steel 14MoV 6 3 in the long-term exposed state (investigated within an European COPERNICUS project) are given in order to demonstrate a possible application of the method. Requirements posed on experimental apparatus and some recommendations for the successful application of the method are presented.

Key words: small punch tests, creep properties, correlation with conventional creep tests

Za določanje preostale življenjske dobe delov termoenergetskih objektov, ki obratujejo pri povišani temperaturi, je potrebno poznati realne mehanske lastnosti brez predolge prekinitve obratovanja objekta. To se lahko doseže z miniaturizacijo vzorčenja (n.pr. z uporabo naprave SSAM) in primernih testnih metod. Osnova preizkusa je deformacija diskastega preizkušanca s konico (penetratorjem) primerne oblike. Uporabljata se dve preizkusni metodi, ena na osnovi konstantne hitrosti (CRP) in druga na sili (CFP) penetracije. Za zanesljivo oceno kritičnih lastnosti je potrebno imeti zanesljive korelacije med temi preizkusi in konvencionalnimi preizkusi na masivnih vzorcih. V tem članku predstavljamo nekaj rezultatov CFP preizkusov na jeklu 14MoV 6 3 (raziskave v okviru EU Copernicus projekta) s ciljem, da dokažemo uporabnost metode. Predstavljene so značilnosti eksperimentalne naprave in dana so priporočila za uspešno uporabo metode.

Ključne besede: small punch preizkus, deformacija z lezenjem, korelacija s konvencionalnimi preizkusi

In order to obtain a maximal time of reliable service of thermal power facilities, great attention is devoted in the last years to a determination of the residual life of exposed parts of the equipment. For this purpose, procedures and techniques are developed allowing to evaluate the actual state of damage of such parts and, on the basis of the evaluation, to estimate the reliability of the parts for further service. It is apparent that the application of the techniques must not damage the integrity of the parts or the damage must be quite negligible. Such techniques can be therefore classified as nondestructive methods.

Small punch test using specimens in shape of a small and thin disc prepared from a small amount of material detracted directly from the exposed parts can also be classified as a nondestructive method. In the test a small puncher is penetrated through the disc specimen into a hole. Two types of this test method seem to be very perspective for the use at higher temperatures. First, the test in which the puncher penetrates through the disc at a given constant rate of deflection (i.e., the central deflection measured in the direction perpendicular to the disc) and the necessary force is measured. The test is termed as CRP (constant rate of penetration) and present a certain analogy to the conventional tensile test. Second, the CFP (constant force of penetration) test in which the puncher penetrates under a constant force and the time dependence of the deflection is measured. The test is
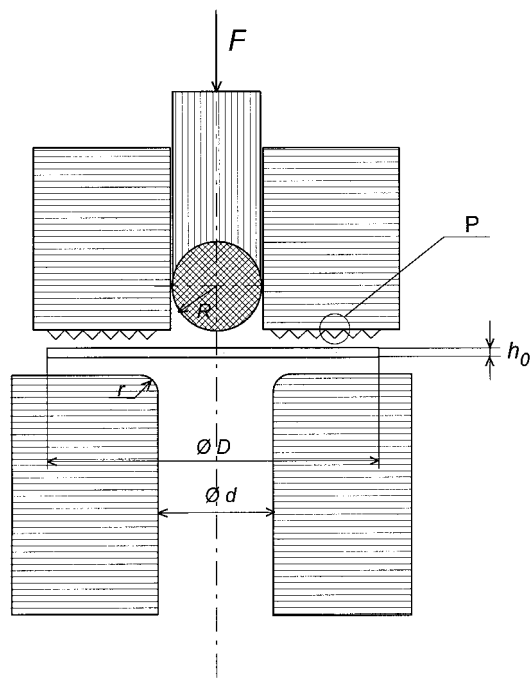
F ...... force of the penetrating
R ..... radius of the ceramic ball, h_0 ..... disc thickness, D ..... disc diameter,
d ..... diameter of lower die, r ...... radius of the camber
P ..... alternative use of circle grooves for a gripping of the specimen

Figure 1: Scheme of the arrangement for small punch tests
Slika 1: Shema naprave za small punch preizkus

similar to a conventional creep test. Both tests are run to the bursting of the disc. As a rule, the puncher is a ball or a bar with a hemispherical tip. In an application in the field of thermal power production, the tests are performed at elevated temperatures and, as a rule, in a protective atmosphere. The scheme of a possible punching arrangement applicable for both test types is illustrated in **Figure 1**.

Small punch tests on miniaturized discs, namely CRP tests, were already applied in specific fields for the determination of the mechanical properties (for a survey see [1]), especially for the determination of the transition temperature between ductile and brittle fracture[2]. The applications were limited so far. Recently, a brief information has appeared concerning the application of CRP test in measurements of fracture toughness and in an assessment of further safety of service of power plants rotors (see Internet, *http://www.epri.com/srd/97spring/04-not. html*). It seems however, that the more detailed information of this application is rather secret.

Early in the nineties, the small punch tests of CFP type were applied in an investigation of creep properties of heat-resistant steels. Fundamental studies were performed at the Swansea University[3] and later in the research institute of the steel plant VITKOVICE[4]. From 1995 to 1998, a COPERNICUS project[5] aimed to the validation of CFP tests in an assessment of residual life of service exposed components was successfully achieved. In the project laboratories from Italy (CISE Milano and JRC Ispra), Slovenia (IMT Ljubljana), Poland (IMMT Krakow) and Czech Republic (IPM ASCR Brno) were managed by MPA Stuttgart, Germany. A substantial amount of the CFP tests was performed by IPM Brno and IMT Ljubljana. The results obtained in the project can be briefly summarized as follows:

 - Experiments consisted of conventional creep tests and CFP tests were performed in two test-exposed steels of type X20CrMoV 12 1 and 14MoV 6 3;
 - In the CFP tests, the small punch apparatus parameters were: 2R = 2.5 mm, d = 4.0 mm, D = 8 mm and h_0 = 0.500 mm (cf. **Figure 1**);
 - An example of typical time dependence of the specimen deflection is illustrated in **Figure 2**. The shape of the dependence is very similar to the shape of conventional creep curves. The initial instantaneous deflection depends on the acting force and enhanced primary creep is in great extent located in the early stage of the test. This fact requires very quick recording of the start of the test (at least 60 sec). A special software was used for the test (program PUNCH, IPM, ASCR Brno). The secondary stage of the curve with the minimum deflection rate is very narrow. After a tertiary stage with an accelerated deflection rate, the tests are ended by the rupture caused by the total ball penetration. In the used experimental arrangement, the rupture occurred at deflections ranging from 1.5 to 2.5 mm;
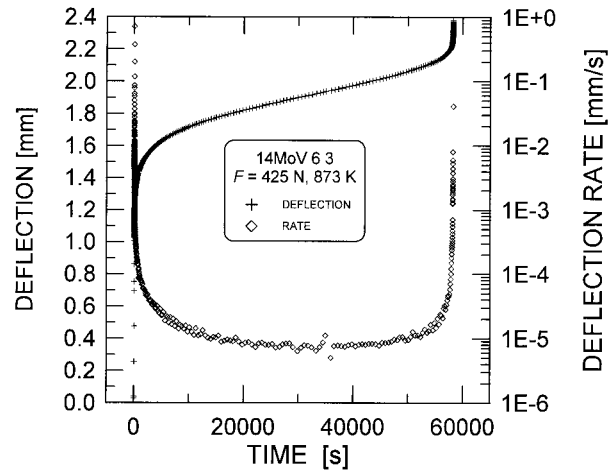
Figure 2: Example of a small punch CFP test
Slika 2: Primer CFP small punch preizkusa

 - Close relations between some characteristics of the CFP and the conventional creep tests were established - though, only in a narrow interval of temperature (813-923K). The total time of more than 110 CFP tests performed on both steels investigated in the creep laboratory of IPM Brno overreached 12000 hrs. Let us present shortly some results obtained in these tests.

In **Figure 3**, the dependence of time to fracture t_f of conventional and CFP tests at 873 K on applied stress σ and force F, respectively, is plotted for the steel 14MoV 6 3. The results of the conventional creep tests at constant load were kindly provided by dr. B. Ule of the IMT Ljubljana. The exponent n_{CON} and n_{CFP} characterizing the stress and force dependence of t_f and defined as

$$n_{CON} = \frac{\partial \ln t_f}{\partial \ln \sigma} \quad \text{and} \quad n_{CFP} = \frac{\partial \ln t_f}{\partial \ln F}, \qquad (1)$$

reach similar values, n_{CON} = -10.36 and n^{CFP} = -12.32

In the following **Figure 4**, the dependence of time to fracture on the reciprocal product of absolute temperature and the universal gas constant R is illustrated for both, conventional creep tests at constant stress 130 MPa and small punch tests at constant force 350 N. The apparent activation energies

$$Q_{CON} = \left[\frac{\partial \ln t_f}{\partial (1/RT)} \right]_\sigma \quad \text{and} \quad Q_{CFP} = \left[\frac{\partial \ln t_f}{\partial (1/RT)} \right]_F, \qquad (2)$$

reach also similar values, Q_{CON} = 378 kJ/mol and Q_{CFP} = 323 kJ/mol. The similarity was also established for the minimum creep rate in conventional tests and the minimum deflection rate in small punch CFP tests.

Figure 5 confirms the validity of the Monkman-Grant relation between the time to fracture t_f and the minimum creep rate $\dot{\varepsilon}_{min}$ for conventional creep tests

$$t_f = K \, (\dot{\varepsilon}_{min})^{-m} \qquad (3)$$
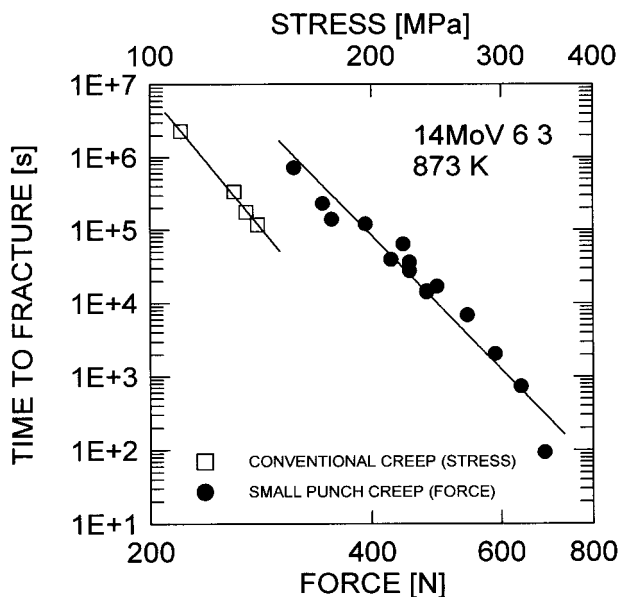
Figure 3: Dependence of time to fracture on force in small punch CFP test (lower scale) and on initial applied stress in conventional constant load creep test (upper scale)

Slika 3: Odvisnost med časom do zloma pri CFP small punch preizkusu (spodnji del slike) in začetno obremenitvijo pri konvencionalnem preizkusu lezenja s stalno obremenitvijo (zgornji del slike)

The value of the exponent m = 0.877 was obtained by constant stress tests of the steel 14MoV 6 3.

In **Figure 6** is plotted the dependence of the time to fracture t_f and the minimum deflection rate $\dot{\delta}_{min}$, obtained from all data of the CFP tests for the steel 14MoV 6 3. The dependence can be well described by a modified Monkman - Grant relation, i.e.,

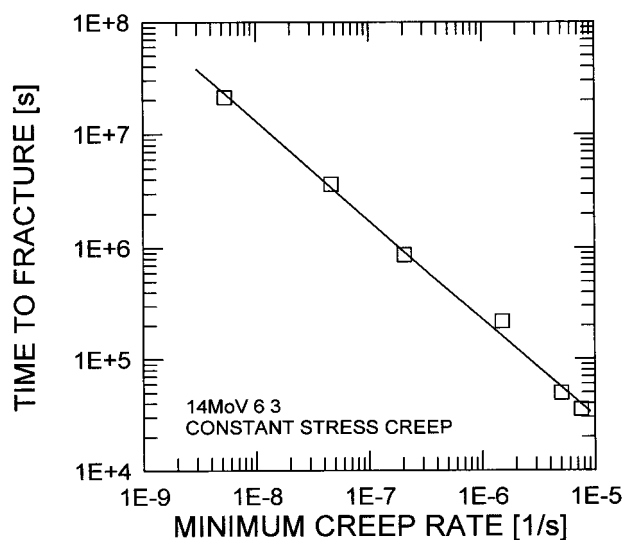$$t^f = K \, (\dot{\delta}_{min})^{-m'} \tag{4}$$
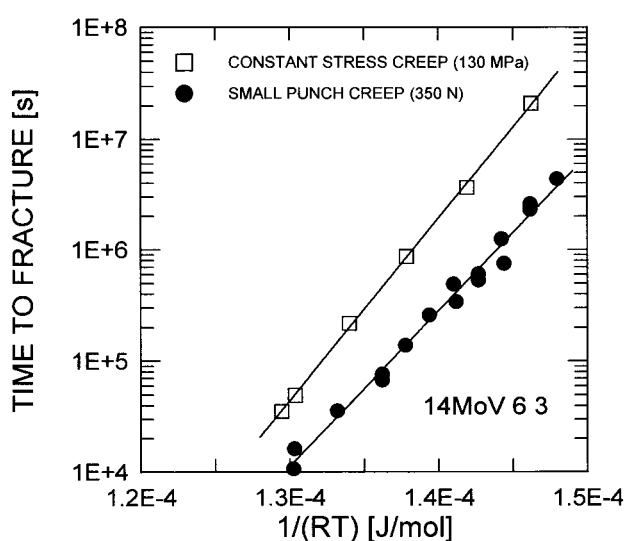
where m' = 0.925.

The results obtained in the COPERNICUS project confirm for both steels investigated - the close relations between the results of the conventional creep tests and the CFP tests. Now, the question must be answered, how this conclusion can be applied in the assessment of the residual or guaranteed life.

Currently, an assessment of the residual life of a construction part is based mostly on data of conventional tests on bulk specimens and CFP tests data cannot be used directly for the assessment. Therefore, an indirect way must be used. Apparently, if the relations between results of the CFP (small punch) and conventional creep tests are known, it is possible to estimate data of the conventional tests necessary for an application of the modern procedures from a suitable set (matrix) of the CFP tests. It must be pointed out that such approach requires the knowledge of the most rigorous forms of these relations. In a common, it is possible to relate the applied stress σ in conventional tests and the force F in the CFP tests corresponding to the same time to fracture t_f.

The formulas for the recalculation of force F to stress σ which are given in references are based either on the reference stress method[6] or on a simple geometry of the plastic flow[7]. Whereas the first method is valid for small deflections only, the second method is critically dependent on the knowledge of contact angle between the puncher and the specimen.

In the following an empirical comparison of the results of CFP small punch test and the conventional creep test will be presented. If the dimensional formalism of the reference stress formula is respected, the quantities are related by

$$\sigma = \frac{F}{10.6h_0^2} \tag{5}$$

Figure 4: Dependence of time to fracture on the reciprocal product of absolute temperature and universal gas constant

Slika 4: Odvisnost med časom do zloma in recipročno vrednostjo produkta temperature in plinske konstante

Figure 5: Dependence of time to fracture on minimum creep rate for constant stress creep tests

Slika 5: Odvisnost med časom do zloma in minimalno hitrostjo lezenja za preizkus lezenja pri konstantni napetosti
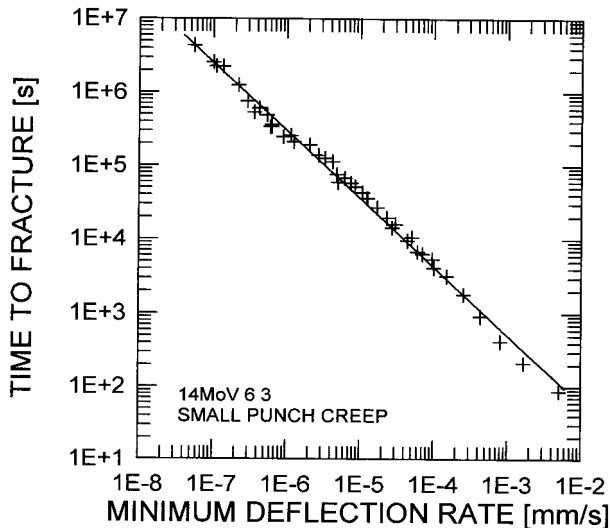
Figure 6: Dependence of time to fracture on minimum deflection rate for small punch CFP tests
Slika 6: Odvisnost med časom do zloma in minimalno hitrostjo globljenja pri CFP small punch preizkusu

Preliminary tests of low alloyed steel performed within the present project have shown that the dependence of time to rupture on the initial specimen thickness can be described by the power function with the power approximately equal to - n_R. A linear dependence of σ/F on $1/h_o$ is thus more probable. Bearing this fact in mind the relation of the two tests can be expressed as

$$\sigma = \frac{F}{2.6\delta_R h_0} \qquad (6)$$

where δ_R is the rupture deflection. In practice, we must assume that the relations between data of conventional and CFP tests may not be general and their specific form will depend on the type of the steel, i.e., the parameters of the relations will differ at least quantitatively in various steels. The relations will be apparently influenced by the parameters of the CFP apparatus, i.e., dimensions of the arrangement (**Figure 1**), specimen shape and its holding in arrangement. Let us mention briefly some examples of possible influences. As a critical influence, we must assume relations among the puncher radius R, the specimen thickness h_o and the lower die diameter d; these relations will determine whether the mode of the test will be purely bending or partly shearing. Further, with respect to possible microstructural mechanisms acting in the deflection and rupture of the specimen, it will be necessary to analyze the influence of the relation between the specimen

thickness h_o and the grain size of the steel. Regarding the low thickness of the specimen, a necessity of protective atmosphere in long-term CFP tests must be verified.

From the practical point of view, the procedure of the detraction of a thin and small layer from the surface needed for specimens preparation is very important. A special equipment SSAM was developed for this purpose (see[4] for more details). The locations of the detraction of specimens must be agreed by the designer of a given equipment and the responsible for the service safety.

With respect to the procedure of the specimen preparation, a comparison of properties of specimens prepared from surface layers with properties of specimens from subsurface layers (from the bulk) of the investigated part must be performed, too. At present, this problem is studied in the IPM Brno[8].

The actual knowledge of possibilities of both type of small punch tests in material characterization confirms fully their applicability. However, from available references and other sources, it can deduced that, at present, results of small punch testing at elevated temperatures are not systematically published, though a classified research of the problem is being performed in several institutions (Electric Power Research Institute, Palo Alto, USA, University of Calgary, Canada and Swansea University, GB, Ishikawajima-Harima Heavy Industries Co., Japan, and, newly, in further European institutes which took part in the mentioned COPERNICUS project).

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REFERENCES

[1] G. Lucas, *Met. Trans.*, 21A (1990) 1105

[2] J. M. Baik, J. Kameda, O. Buck, *Scripta met.*, 17 (1983) 92

[3] J. D. Parker and J. D. James, *Prof. Fifth Int. Conf. on the Creep and Fracture of Engineering Materials and Structures*, The Institute of Metals, London 1993, p. 651

[4] J. Purmensky, V. Kupka, *Hutnické listy*, 48 (1993) 65

[5] Small Punch Test Method Assessment for the Determination of the residual Creep Life of Service Exposed Components. *Project COPERNICUS*, Contract ERB CIPA CT94 0103

[6] A. C. McKenzie, *Int. J. Mech. Sci.*, 10 (1968) 441

[7] H. Lippmann: Mechanik des Plastischen Fliessens, Springer-Verlag Berlin, Heidelberg, 1981

[8] Validation of small punch creep tests of surface specimens for prediction of residual life of real construction parts. *Project of Grant Agency of CR 106/98/1363*