Theoretical and Applied Fracture Mechanics xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Theoretical and Applied Fracture Mechanics

journal homepage: www.elsevier.com/locate/tafmec

Recent developments in small punch testing: Applications at elevated temperatures

Petr Dymáček

CEITEC IPM, Institute of Physics of Materials, Academy of Sciences of the Czech Republic, Žižkova 22, 616 62 Brno, Czech Republic

ARTICLE INFO

Article history:
Received 30 June 2016
Revised 15 September 2016
Accepted 26 September 2016
Available online xxxx

Keywords:
Small punch test
Creep rupture
Stress relaxation

ABSTRACT

The paper is focused on summarizing the high temperature tensile, creep and stress relaxation small punch testing (SPT) of ferritic-martensitic steel P92. The relation of SPT results with conventional uniaxial tests results is presented. Two heats of P92 steel with different heat treatment are compared in SPT creep. The finite element modeling of SPT creep setup is compared with experimental SPT results. The stress relaxation SPT is discussed and values of initial stress and residual stress were evaluated from the test. Very good agreement of the stress relaxation SPT, stress relaxation uniaxial test and numerical modeling is shown by their comparison. An overview of the ongoing round robin on creep SPT is briefly outlined.

1. Introduction

Small punch tests (SPT) are using specimens of a thin disc shape prepared from a small amount of material that can be extracted directly from the surface of exposed parts without their damage. In these tests, a punch penetrates through the disc specimen into a hole. The European Code of Practice of SPT has been released in 2007 [1].

Three principal variations of this test type seem to have a good potential for use at elevated temperatures.

First, the test in which the punch penetrates through the disc at a given constant rate of deflection (i.e., central deflection measured in a direction perpendicular to the disc) and the necessary force is measured; this test is marked as CDR (constant deflection rate). It has certain analogy with the conventional tensile test.

Second, the CF test (constant force) is a test in which the punch penetrates under constant load and the time dependence of the deflection is measured. This test is similar to a conventional creep test. Both tests are run up to the rupture of the disc.

Third, the CD test (constant deflection) is the analogy to stress relaxation testing at elevated temperatures. Basically, the specimen has to be loaded at a given deflection rate to a specific central deflection that conforms conditions of the membrane-stretching regime. The deflection of the disc is then held constant and the force relaxes as the elastic strain is replaced by inelastic creep strain. The force vs. time response during relaxation can be recalculated to stress vs. time response, differentiated and divided by elastic modulus to give the creep rate and finally its dependence on the stress.

As a rule, the punch is a ceramic ball or a bar with a hemispherical tip. In application within the field of power- or thermal-generation industry, these tests should be performed at elevated temperatures and they should be conducted in a protective atmosphere (usually argon). A scheme showing the punching arrangement applicable for all three test types is illustrated in Fig. 1.

SPT has undergone a rapid development in recent years especially in experimental setups, introduction of notched specimens and the numerical modeling of SPT. Two detailed reviews on SPT and its modeling were published recently by Rouse et al. [2] and Abendroth and Soltysiak [3]. They show the usefulness of the numerical modeling using the finite element method (FEM), optimization algorithms and inverse analyses for a deeper understanding of the processes during several phases of the disc deformation up to its rupture.

Recently, two other types of the small punch test have emerged: (i) the tested discs are furnished with a precisely machined groove and their testing can then be compared with Charpy notch impact tests [4,5] and (ii) the loading mechanism is adjusted and the acting force is oscillating [6]. In this way, the fatigue mechanisms and fatigue crack propagation can be studied.

The aim of the paper is to present an overview of SPT methods applicable at high temperatures to obtain mechanical properties from very small volume of material and their correlation with the properties by conventional tests. An overview of the ongoing round robin on creep SPT is outlined in Section 4.

E-mail address: pdymacek@ipm.cz

http://dx.doi.org/10.1016/j.tafmec.2016.09.013
0167-8442/

Please cite this article in press as: P. Dymáček, Recent developments in small punch testing: Applications at elevated temperatures, Theor. Appl. Fract. Mech. (2016), http://dx.doi.org/10.1016/j.tafmec.2016.09.013

Nomenclature

F	applied force [N]	R_m^{SPT}	ultimate strength obtained by SPT-CDR [MPa]
F_e	force at yield defined as transition between the linear and plastic bending of the disc [N]	σ	applied stress [MPa]
F_m	maximum force during the SPT-CDR [N]	σ_p	peak stress in the relaxation test [MPa]
F_p	peak force in the relaxation test [N]	σ_r	residual stress in the relaxation test [MPa]
F_r	residual force in the relaxation test [N]	ΔF	decrease of force in the relaxation test [N]
h_0	initial disc thickness [mm]	$\Delta\sigma$	decrease of stress in the relaxation test [MPa]
u	deflection of the disc [mm]	f	friction coefficient [–]
u_m	deflection of the disc at F_m [mm]	t_r	time to rupture in the creep test or SPT-CF [s] or [h]
$\dot{u}_{min}$	minimum deflection rate [mm/s]	t_{relax}	time of relaxation [s] or [h]
$\dot{\varepsilon}_{cr}$	creep strain rate [1/s]	Ψ	SPT parameter [N/MPa]
R_e^{SPT}	yield strength obtained by SPT-CDR [MPa]	k_{SP}	SPT material parameter [–]

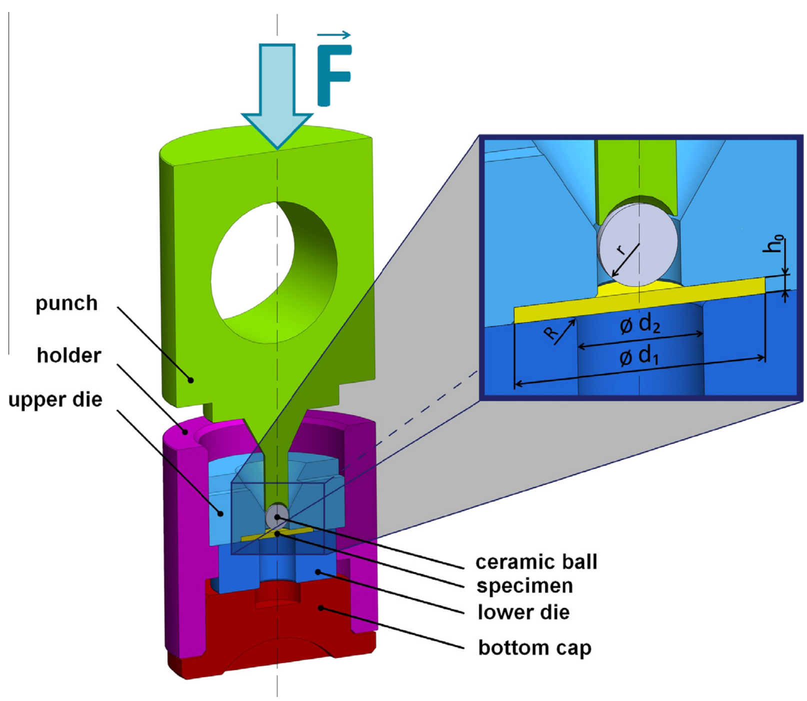

Fig. 1. SPT setup, $r = 1.25$ mm, $h_0 = 0.5$ mm, $R = 0.2$ mm, $d_1 = 8$ mm, $d_2 = 4$ mm.

2. Materials and procedures

Two different heats of P92 steel were studied by SPT:

(i) P92 NT (normalized and tempered) forged experimental ring with the wall thickness of 82 mm manufactured by ŽĎAS a.s. The chemical compositions are shown in Table 1. The P92 NT heat treatment consisted of normalization annealing (1060 °C/1 h) followed by tempering (760 °C/2 h/air).
(ii) P92 RR (round robin) steam pipe outer diameter of 219.1 mm with wall thickness 22.2 mm, manuf. no. 40038698 made by Třinecké Železárny a.s. The P92 RR was in as received state after pipe manufacture.

The P92 NT disc specimens of 8 mm diameter were prepared at IPM Brno from cylinders with axis oriented in radial direction. The cylinders were sliced in an electro discharge machine to thickness of 1.1 mm and then ground on metallographic paper under water to thickness of 0.5 ± 0.005 mm. This procedure should prevent any changes in microstructure on the disc surface.

The P92 RR discs from as received pipe were prepared in laboratories of MMV Company, Ostrava, Czech Republic from a layer 2–3 mm under the pipe outer surface to simulate the sampling (scooping) process.

As presented in [7] the SPT-CDR of P92 NT steel was performed in a SPT adapted lever arm creep machine equipped with furnace flushed by purified argon atmosphere and a stepping motor that allows continual loading of the specimen via dead weight on a moving table. Selected deflection rate for CDR experiments was 0.25 mm/min. The P92 NT steel was tested by 5 specimens at room (RT) and elevated temperatures 500 °C and 600 °C. The SPT-CF [8,9], SPT-CD [7] of P92 NT steel and SPT-CF of P92 RR steel were performed in the same type of adapted creep machine at 600 °C. Relative movement of the punch and reversal cage was measured by a linear variable differential transformer (LVDT). The force was measured by a 1 kN load cell on the load train dead weight side of the creep machine. Ceramic ball of 2.5 mm diameter from Frialit® F99.7 was used as a punch tip and the parts of arrangement shown in Fig. 1 were made from Inconel 713. The SPT-CF of P92 NT steel were done in range of force from 400 to 700 N. The SPT-CF of P92

Please cite this article in press as: P. Dymáček, Recent developments in small punch testing: Applications at elevated temperatures, Theor. Appl. Fract. Mech. (2016), http://dx.doi.org/10.1016/j.tafmec.2016.09.013