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SMALL-PUNCH TESTING OF A WELD'S HEAT-AFFECTED ZONES

TESTIRANJE LEZENJA TOPLOTNO VPLIVANIH PODROČIJ VARA Z UPORABO MAJHNEGA BATA

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Small-punch creep tests were performed on four different zones of a P91 welded joint: the base metal (BM), the weld metal (WM), the heat-affected zone on the base-metal side (HAZ-BM) and the heat-affected zone on the weld-metal side (HAZ-WM). In addition to the creep-rupture times, full creep-deflection curves were also available, from which the creep properties of different HAZ zones could be derived.

In this paper an analytic approach based on Chakrebarty's membrane-stretch model and Kachanov's creep law is used to interpret the creep-deflection curves of different zones. First of all, the strains and stresses are derived from the observed deflection curves according to Chakrebarty's membrane-stretch model, then the Kachanov parameters are determined by attempting to minimize the sum of the squares of the residuals (the difference between the derived strains and the calculated strains at each time point). With the Kachanov parameters known, all the creep properties of the different zones of the welded joint can be obtained.

Keywords: small punch creep tests, welded joint, Kachanov parameters

Preskušanje lezenja z majhnim batom je bilo opravljeno na štirih različnih področjih P91 varjenega spoja, in sicer na osnovnem materialu (BM), na varu (WM), na toplotno vplivnem področju na strani osnovnega materiala (HAZ-BM) in na toplotno vplivnem področju na strani vara (HAZ-WM). Poleg samih časov lezenja do loma so na razpolago tudi celotne krivulje upogib preizkušanca–čas, na osnovi katerih je možno določiti lastnosti lezenja različnih toplotno vplivnih področij.

V prispevku smo uporabili analitičen način interpretacije krivulj lezenja (odvisnost upogib preizkušanca–čas) preizkušancev, vzetih iz različnih območij varjenega spoja P91. Analitični način temelji na Chakrebartyjevem modelu raztezanja membrane in na Kachanovem zakonu lezenja. Najprej se iz časovno odvisnih krivulj upogibanja preizkušanca izračuna napetosti in deformacije po Chakrebartyjevem modelu raztezanja membrane. Potem se določijo Kachanovi parametri z minimiziranjem vsote kvadratov ostankov (to je razlika med dobljenimi raztezki in izračunanimi raztezki v vsaki časovni točki). Ko poznamo Kachanove parametre, lahko ocenimo vse lastnosti lezenja posameznega področja varjenega spoja.

Ključne besede: preskušanje lezenja z majhnim batom, varjeni spoj, Kachanovi parametri

1 INTRODUCTION

Reducing the consumption of energy by improving the efficiency of thermal power plants has become an important issue in the development of modern materials. Advanced power plants need to use higher working temperatures and higher steam pressures, and this requires materials with superior properties that can operate under such conditions [1,2]. The creep properties of new metals for high-temperature applications, i.e., for the welded components of power plants with higher steam temperatures and pressures, are extremely important. These materials exhibit a pronounced change in their microstructure during exposure to high-temperature service conditions, which determines their remnant creep life. It is important to remember that it is necessary to achieve good creep resistance for the welded joint as a whole, and not just for the welding consumables. Experience has shown that the first cracks always appear in the welded joints, and so the creep properties for different HAZs are very important for the life assessment of welded structures [3].

The creep properties of a welded joint can be measured with cross-weld specimens [4,5]; however, the ongoing micro-mechanisms in particular zones of a welded joint cannot be identified for certain. Therefore, a new creep-measuring technique, known as small-punch creep testing (SPCT), can be used. As only a small amount of material is needed for SPCT, this represents a new method for determining the creep properties for a weld's HAZs. The SPCT was carried out on P91 steel at the Institute of Metals and Technology, Ljubljana, Slovenia. This paper describes how to derive the creep properties from the SPCT curves.

2 EXPERIMENTAL PROCEDURE

The creep examination procedure for the P91 welded joint can be described as follows. High-alloyed P91 consumables were used for welding (a modified J-type weld, i.e., a half V-shape) the two parts of the main steam pipes manufactured from the same P91 steel. The welded joint was then tempered for 1000 h at 565 °C in order to relieve the internal stresses and to simulate the

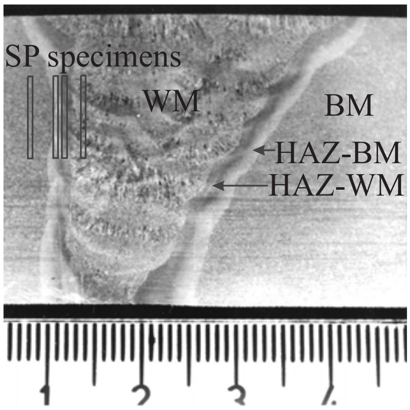

Figure 1: Welded joint of P91 base metal and P91 weld metal.
Slika 1: Varjeni spoj P91 osnovnega materiala in P91 varjenega materiala

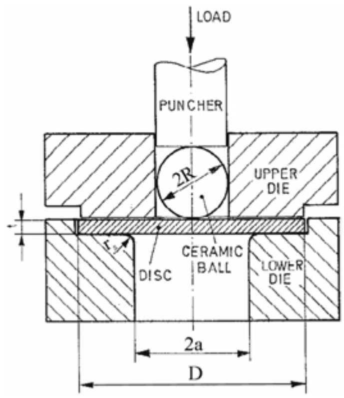

Figure 2: Schematic illustration of the dies in the small-punch creep-test equipment.
Slika 2: Shematični prikaz čeljusti pri napravi za preskušanje lezenja z majhnim batom

operating conditions in the material where no external stress is applied. The SPCT specimens were cut from the base material, from the HAZ and from the weld itself (**Figure 1**). The undiluted all-weld metal chemical composition for the experimental consumables is shown in **Table 1**.

The SPCT technique was used for the creep test with a disk-shaped test specimen that was cut from the weld with a diameter of 8 mm and a thickness of 0.5 mm. As shown in **Figure 2**, the small-punch test equipment used is similar to a constant-load cantilever creep machine. The test specimens are placed on the central axis of the lower die of the specimen holder and fixed by the upper die so that there is a loose fitting, i.e., neglecting the friction between the upper die and the specimen. The ball and the puncher are inserted into the hole in the upper die of the holder. The assembled holder is then put into reverting grips and suspended in the creep machine. During the test a constant load acts on the specimen by means of a ceramic ball with radius R = 1.25 mm. The radius of the hole, a, is equal to 2 mm, and its shoulder radius, r_s, is equal to 0.2 mm. The temperature of the specimen is measured by means of a thermocouple placed very close to the specimen. The displacement of the puncher, i.e., the central deflection of the disk specimen, is measured using a very accurate inductive transducer (repeatability of 1 μm), and is recorded continuously with a computer. A constant load of 520 N and a test temperature of 620 °C was applied during the SPCT.

2.1 Experimental Testing Results

The results of the SPCT are summarized in **Table 2**, including the rupture time and the deflection at rupture.

Table 2: Test results of SPCT
Tabela 2: Rezultati SPCT

	Rupture time t_r/h	Deflection δ/mm due to load	Deflection δ_r/mm at rupture
BM	20.094	1.531	2.467
WM	22.504	0.904	2.287
HAZ-BM	8.286	1.743	2.584
HAZ-WM	16.556	1.343	2.664

The deflection curves of four different zones of the P91 welded joint are shown in **Figure 3**. The load was added at one time within 3 seconds and the applied stress is higher than the yield strength. Taking into account the influence of plasticity, the deflection due to load can be determined from the intersection point of two lines: the

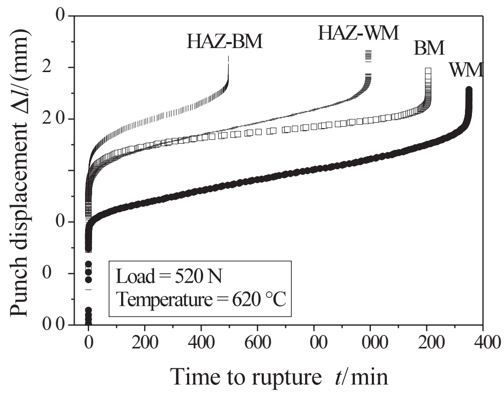

Figure 3: SPCT deflection curves of four different zones of the P91 welded joint
Slika 3: SPCT krivulje upogibanja za štiri različne cone P91 varjenega spoja

Table 1: Chemical composition of P91 material
Tabela 1: Kemična sestava materiala P91

	C	Si	Mn	P	S	Cr	Mo	V	Ni	Nb	N
w/%	0.10	0.27	0.53	0.007	0.01	8.76	0.91	0.2	0.35	0.04	0.0038

tangential line of the initial load deflection and the tangential line of the creep deflection. The deflections due to the load for four different zones are also listed in **Table 2**.

3 STATE OF THE ART FOR THE DETERMINATION OF CREEP PROPERTIES

Until now there has only been a little work on interpreting the creep curves from SPCT. In this paragraph, one of the existing approaches is described first.

3.1 Equivalent stress concept

The basic idea of the equivalent stress concept is to answer the question: "What load should be used in the SPCT to obtain the same time-to-rupture as in a 1-D conventional constant-load test?"

In total, four equations were found in the literatures [6,7,8], which are listed in the round-robin report [9]. The symbols used are listed as follows (see **Figure 4** for details):

F_{sp}: applied load on the SPCT specimen
t : thickness of the disc
t_0: initial thickness of the disc
a: radius of the disc between supports
R: radius of the punch
r: current radius
σ: membrane stress
φ: angle made by the surface normal to the vertical axis
θ: angle φ at $r = a$
θ_0: angle φ at the contact boundary
δ: central deflection of the disc

One of the formulations proposed by Chakabarty was for stretch forming over hemispherical punch heads as [8]:

$$\frac{F_{sp}}{\sigma} = 2\pi R t \sin^2 \theta_0 \qquad (1)$$

$$t = t_0 \left\{ \frac{1+\cos\theta_0}{1+\cos\varphi} \right\}^2 \qquad (2)$$

where t is the current specimen thickness and t_0 is the initial thickness.

3.2 Relations between strains, stresses and deflections

With the increasing deflection the disc shows an extension of the fibers on the tensile side. Tettamanti and Crudeli proposed that the extension of the arc, which insists on the same chord, can be calculated using a simple geometric diagram. The creep strain rate of the fibers on the tensile side of the disc can be derived from the deflection curve [6]. This idea was adopted by Yingzhi Li to derive the creep strain from the deflection and obtain the creep properties [10].

A better expression of the relation between the strain ε and the central deflection δ was proposed by Chakrabarty based on the so-called membrane-stretch model for the stretch forming of a circular blank over a hemispherical punch head. It is assumed that the rigid punch is well lubricated in order to neglect the effect of friction; it was also assumed that the material was rigid-plastic. In addition, the deformation of the disc was assumed to take place under membrane stresses alone because the thickness of the disc was small in comparison to the radius of the punch. According to Chakrabarty, the general formula for compressive thickness strain is [8]:

$$\varepsilon = 2 \ln \frac{(1+\cos\varphi)(1+\cos\theta)}{(1+\cos\theta_0)^2} \qquad (3)$$

The maximum strain at the centre of the disc ($\varphi = 0$) is:

$$\varepsilon = 2 \ln \frac{2(1+\cos\theta)}{(1+\cos\theta_0)^2} \qquad (4)$$

The strain at the contact boundary ($\varphi = \theta_0$) is:

$$\varepsilon = 2 \ln \frac{(1+\cos\theta)}{(1+\cos\theta_0)} \qquad (5)$$

Chakrabarty proved that the radius strain ε_r is equal to the circumferential strain ε_c, together with the volume incompressible condition; the compressive thickness strain ε turns out to be the equivalent strain.

Meanwhile, Chakrabarty gave the expression for the central deflection of the disc, which equals the value of z at $\varphi = 0$ (**Figure 4**), as:

$$\delta = a \sin\theta \ln \frac{\tan(\theta_0/2)}{\tan(\theta/2)} + R(1-\cos\theta_0) \qquad (6)$$

An equation relating θ and θ_0 is shown as:

$$\sin\theta = \frac{R}{a} \sin^2 \theta_0 \qquad (7)$$

Zhen Yang and Zhiwen Wang [11] gave the relation between the maximum equivalent strain ε at the disc center and the deflection δ from Equations (4)–(7). A set of ε and δ values are computed by inputting the actual specimen sizes a and R, and setting θ_0 to values in the

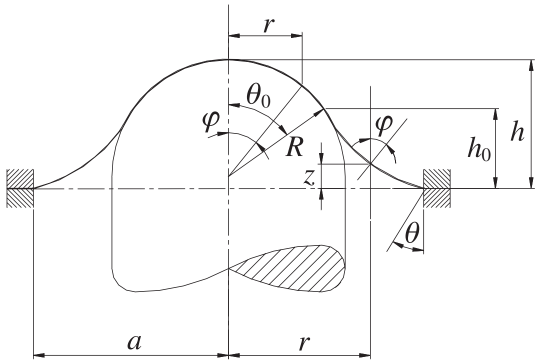

Figure 4: Geometry of deformation [8]
Slika 4: Geometrija deformacije diska [8]

range from 0 to 90°. Then by fitting the values of ε and δ using a polynomial expression, a relationship between ε and δ (in units of mm) is finally obtained. Zhen Yang and Zhiwen Wang also gave the relation between the stress σ and the deflection δ using an exponential expression.

The strain ε at the contact boundary is more important than that at the disc center, as the former can be used to derive the stress σ at the contact boundary with the strain-hardening law. From Equations (4)–(7) and a similar procedure to that mentioned above, the relation between the equivalent strain ε at the contact boundary and the deflection δ is built with a polynomial fitting. For the European round-robin [9], the specimen dimensions were a = 2.0 mm and R = 1.25 mm. The relationship between the equivalent strain ε at the contact boundary and deflection δ (in units of mm) is expressed as follows.

$$\varepsilon = 0.14718\delta + 0.03653\delta^2 + 0.00772\delta^3 \tag{8}$$

A general relation between F_{sp}/σ and the deflection δ can be derived from the equilibrium equation (1) together with Equations (6) and (7). The relationship between F_{sp}/σ (F_{sp} in units of N, σ in units of MPa) and deflection δ (in units of mm) is expressed in the form

$$F_{sp}/\sigma = 1.26613\delta - 0.12866\delta^2 - 0.04344\delta^3 \quad (\text{for } \delta > 0.8 \text{ mm}) \tag{9}$$

When the deflection δ tends to zero, F_{sp}/σ also tends to zero, i.e., the membrane stress σ tends to infinity. Thus the formula is not valid in the small-deformation stage as the bending is neglected. Based on an engineering judgment, the results of a large deformation are valid if the deflection is larger than 20 % of the maximum structural dimension. Therefore, the stresses given by Equation (9) are valid, even in creep analysis, if the deflection is larger than 20 % of the hole diameter, i.e., 0.8 mm.

4 AN ANALYTIC PROCEDURE TO DETERMINE THE CREEP PROPERTIES

The analytical procedures represent a critical aspect of the interpretation of SPCT. The procedures consist of the following steps:

1. Derive strains and stresses from the observed deflection curve according to the membrane-stretch model provided by Chakrabarty.
2. The Kachanov parameters can be estimated by attempting to minimize the sum of the squares of the residuals (difference between the derived strains and the calculated strains at each time point) considering the stress variation.
3. By using Kachanov's obtained parameters, determine the creep properties at the test temperature.

4.1 Kachanov model

The finite-element package ANSYS 5.7 is used in the calculations. In ANSYS the standard creep laws only contain the primary and the secondary creep regions. This means that a user-defined creep law is needed in order to be able to describe the tertiary creep region. The Kachanov creep law is used to define the total creep behavior in the calculation.

According to the Kachanov model, a creep curve can be governed by the following coupled equations (for details see [12]):

$$\dot{\varepsilon} = At^{-m}\left(\frac{\sigma}{1-\omega}\right)^{n} \tag{10}$$

$$\dot{\omega} = Bt^{-m}\,\frac{\sigma^{\nu}}{(1-\omega)^{\eta}} \tag{11}$$

In which A, B, n, ν and η are the Kachanov parameters; ω denotes the damage factor, ω = 0 for untouched and ω = 1 for failure. For a constant-stress situation, the coupled equations (10) and (11) can be solved by integration and give explicit expressions for the strain ε and the damage ω, see [12] for details.

By knowing the Kachanov parameters, the creep properties of the material can be determined. For constant-stress conditions, Equations (10) and (11) can be integrated to give:

$$\varepsilon = \varepsilon_R\left\{1-\left[1-\left(\frac{t}{t_R}\right)^{1-m}\right]^{1-\frac{n}{\eta+1}}\right\} \tag{12}$$

Where

$$t_R = \left[\frac{1-m}{B(\eta+1)\sigma^{\nu}}\right]^{\frac{1}{1-m}} \tag{13}$$

(14)

Here, A, B, n,ν, η and m are the six Kachanov parameters. If the primary creep stage can be neglected, then the parameter m = 0, and the number of parameters is five.

With the Kachanov parameters known, the creep properties of the material can be determined as follows. The minimum creep strain rate will be:

$$\dot{\varepsilon}_{min} = At^{-m}\sigma^{n} \tag{15}$$

The rupture time t_R and the rupture strain ε_R are already given in Equations (13) and (14) respectively. If the primary creep stage can be neglected, i.e., m = 0, from Equation (15), the creep strain rate can be determined in the form of the Norton creep law.

$$\dot{\varepsilon}_{min} = A\sigma^{n} \tag{16}$$

The rupture time can be derived from Eq. (13) as follows,

$$t_R = \frac{1}{B(\eta+1)\sigma^{\nu}} \tag{17}$$

The rupture strain can be determined from Equations (14) and (15), and the rupture strain can be expressed in the form of the Dobes-Milicka relation [7]:

$$\varepsilon_R = \lambda \dot{\varepsilon}_{min} t_R \tag{18}$$

where

$$\lambda = \frac{\eta+1}{(\eta+1-n)} \tag{19}$$

The obtained material parameters are derived at the test temperature. If a set of creep curves at different temperatures is available, a set of parameters is derived at a different temperature. A least-square method can be used to determine the relations between the material parameters and the temperature. Dorn's equation can be used to describe the temperature dependency. For example, Norton's creep law can be expressed in the form:

$$\dot{\varepsilon}_{min} = A\sigma^{n} \exp\left(-\frac{Q}{RT}\right) \tag{20}$$

4.2 Determination of the Kachanov parameters and the creep properties

First, the strain curves should be checked to ensure a monotonous increase. In the mathematical software package MATLAB there is a function FMINCON that can carry out a non-linear minimization procedure with constrained conditions. However, it is difficult to get the results as the matrix is singular and depends strongly on the starting, estimated values. The practical method is to specify a broad range of parameters and directly carry out the optimization scheme.

It is easy to specify the range for parameters *n, ν* and *η*. They are usually between 3 and 12. The range of parameter *m* is between 0.05 and 1. The Dobes-Milicka constant λ must be greater than 1 and less than 6, thus $\eta > 6/5{*}n{-}1$. It is difficult to specify the range of parameters A and B (from Equations (16) and (17)). The obtained Kachanov parameters are listed in **Table 3**. A comparison of the predicted and observed strain curves for the base metal (BM) is shown in **Figure 5**. Good agreement is found up to the tertiary creep region.

Table 3: Kachanov parameters of test material (at 620 °C)
Tabela 3: Kachanovi parametri preskušanja materiala (pri 620 °C)

Parameter	*A*	*B*	*n*	*ν*	*η*	*m*
BM	2.262×10^{-21}	5.099×10^{-31}	7.235	11.000	8.647	0.844
WM	5.067×10^{-12}	1.082×10^{-11}	3.571	3.571	3.571	0.438
HAZ-BM	7.513×10^{-23}	5.591×10^{-13}	8.143	4.143	9.857	0.693
HAZ-WM	1.628×10^{-24}	1.558×10^{-17}	8.714	5.857	11.000	0.564

Based on the obtained Kachanov parameters, the creep properties of the test material can be derived if the primary creep is neglected. Taking the base metal (BM) as an example:

The Norton creep law:

$$\dot{\varepsilon}_{min} = A\sigma^{n}$$

with $A = 2.262 \times 10^{-21}$ and n = 7.235

According Equation (17), the rupture time vs. stress:

$$t_R = A' \cdot \sigma^{-n'}$$

With:

$A' = 1/\left[B(\eta+1)\right] = 2.033 \times 10^{29}$ and $n' = \nu = 11000$

According to Equation (19), the Dobes-Milicka constant λ:

$$\lambda = (\eta+1)(\eta+1-n) = 4.0$$

The predicted rupture time vs. stress for the four different zones are summarized and shown in **Figure 6**. From **Figure 6** it is obvious that the weakest part of the P91 weld was the inter-critically quenched HAZ-BM.

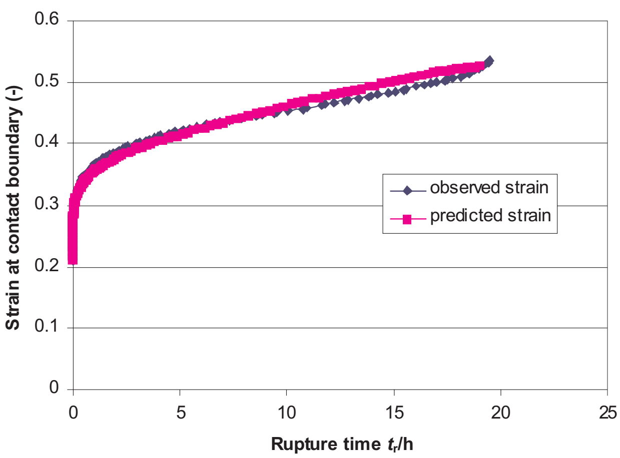

Figure 5: Comparison of predicted and observed creep strains (BM)
Slika 5: Primerjava napovedanih in izmerjenih deformacij lezenja (BM)

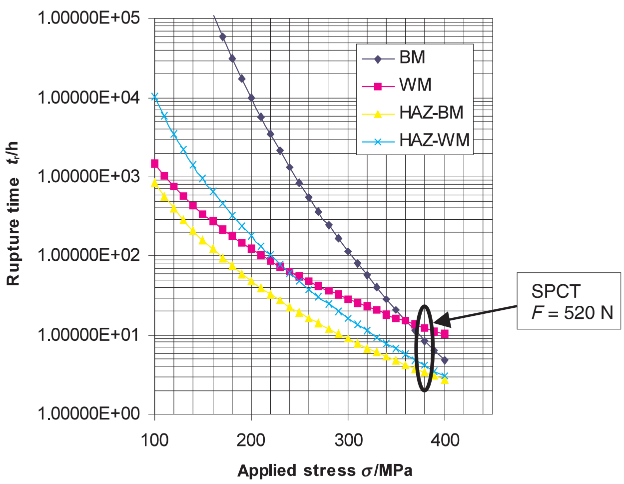

Figure 6: Rupture time vs. stress predicted by SPCT
Slika 6: Odvisnost časa loma vs. napetost, napovedana s SPCT

5 CONCLUSION

Small-punch creep tests were performed on four different zones of a P91 welded joint: the base metal (BM), the weld metal (WM), the heat-affected zone on the base-metal side (HAZ-BM) and the heat-affected zone on the weld-metal side (HAZ-WM). In addition to the creep-rupture times, full creep-deflection curves were also available, from which the creep properties of the four different zones of the P91 welded joint were derived.

Engineering experiences show that the creep properties for the different HAZs are very important for a life assessment of welded structures. However, due to difficulties with the measurement, the creep properties of a weld's HAZ can only be obtained indirectly. The proposed approach provides a non-empirical method to interpret creep-test data from a small-punch test curve, and makes it possible to derive the creep properties for different HAZs. The results of the rupture time vs. stress predicted by the SPCT are shown in Figure 6. Only a few SPCT of different zones of the welded joint are enough to obtain the Kachanov parameters, which can describe/predict the creep properties of these different zones of the welded joint over a wide range of applied stresses. This might be a new approach to determining the creep properties for the weld's HAZ as only a small amount of material is needed for small-punch creep tests.

A verification should be carried out to compare the results of the small-punch and standard 1-D uniaxial creep tests. The 1-D creep tests of the P91 base metal are now in progress.

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