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# Determination of creep properties from small punch test using experimental correlation

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**Abstract:** The correlation of the small punch creep (SPC) test results with uniaxial creep test results is challenging due to several factors. The stress state is equibiaxial in the SPC test and the equivalent stress is not constant as the punch is advancing into the disc. The classical use of Chakrabarty membrane theory, with a constant  $F/\sigma$  ratio, is useful for rough estimates of equivalent stress but for more accurate estimations the strain hardening effect has to be accounted for. A new advanced method is introduced in this paper clearly showing robustness and good predictability in estimating short term uniaxial creep strength from SPC results. The equivalent stress in SPC can be estimated using equal rupture time as a base or by converting SPC deflection rate to equivalent uniaxial creep strain rate. The current study is using a large test data pool and the obtained empirical formulas are shown to reliably estimate equivalent stress for time to rupture predictions and the parameters for the Norton minimum creep rate law.

**Keywords:** creep; uniaxial; small punch; heat resistant steels

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## 1. Background

In the early 1980's, the small punch test technique was developed in USA and Japan [1, 2]. This technique has been applied to nuclear reactors, electric power plants for safety assessments. European researchers have carried out the pioneering work on small punch creep testing (SPC), i.e. testing at constant force, in the 1990's [3-4]. The European Code of Practice (CoP) document has become available in 2006 [5], which provides a guide line to perform small punch tests for metallic materials, and introduces methods for estimation of tensile properties, fracture toughness and creep properties. At present, small punch testing is used for various applications to a broad range of materials including developed lightweight materials [6-20].

The application of the small punch test in practice is critically sensitive to the existence of a reliable procedure for comparison with the results of conventional creep tests. In the European Code of Practice, a rough estimate of the conversion between force  $F$  in small punch test and stress  $\sigma$  in conventional test was made using the Chakrabarty membrane stretch model [21] giving a constant ratio of  $\Psi = F/\sigma$ . The Chakrabarty ratio for the standard SP specimen geometry (initial specimen thickness  $h_0 = 0.5$  mm) is  $\Psi = 1.8908$  N/MPa [22, 23]. The ratio can be used for planning test load but it is not suitable for creep property assessment. If Chakrabarty model is used to predict the creep properties, the difference between the prediction and the uniaxial tests are commonly reported [23-28]. It has been shown that the  $\Psi$  ratio is not a constant but depends on both stress and temperature. The temperature and force dependence mainly originates from the effective area under the punch during the test.

The complexity of the SPC test consists in the inclusion of several non-linear problems: the geometrical non-linearity due to large deformation, the physical nonlinearity due to plasticity and creep and the contact nonlinearity due to the contact area between the punch and the specimen. Recently it has been found that the creep behaviour in SPC is also influenced by excessive plasticity during the loading [29].

In order to solve these problems, efforts have been made to improve the interpreting approach for SPC, and several conferences and symposia have been held to exchange ideas and experiences. Due to the complexity of the SPC test itself and a lack of systematic test data for verification, up to now there is no generally accepted method to estimate uniaxial creep properties from it. Now we may wish to review these thoughts, perhaps to obtain some benefits. Finally, we would like to propose a new simple procedure based on a detailed analysis of deflection *vs.* time curves available in parallel with the uniaxial creep data.

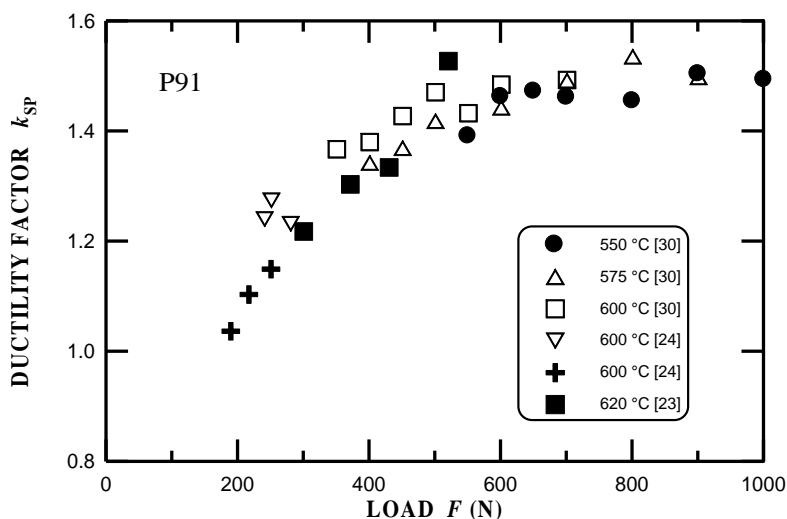
### 1.1 Formula of European Code of Practice

In the European code of practice (CoP) [5], a formula was put forward to estimate the membrane stress  $\sigma$  based on the Chakrabarty membrane stretch model

$$F / \sigma = 3.332k_{SP}a^{-0.2}R^{1.2}h_0 \quad (\text{for } u > 0.8 \text{ mm}) \quad (1)$$

where  $a$  is radius of lower die,  $R$  is punch radius and  $u$  is deflection (in mm).  $k_{SP}$  is a correlation factor introduced to adjust the theoretical model to the experimental results. A question is raised, how to estimate the value of  $k_{SP}$ ?

Blagoeva in her Ph. D. thesis carried out an investigation on new P91 base metal and service exposed metal, where both SPC and conventional uniaxial tests were performed [24]. By using the test results provided by JRC [24] and IMT Slovenia [23], the equivalent stresses can be derived from the rupture time in SPC with the uniaxial data. By substitution of the obtained equivalent stress into Eq. (1), the  $k_{SP}$  is found to be 1.1 to 1.5, see Fig.1 for details. In the figure, the additional data obtained on various heats of P91 steel are presented [30]. The ductility factor  $k_{SP}$  is obviously increasing with the increasing force and it is probably also dependent on the test temperature. Two effects, the large deformation effect and the strain hardening effect, can be suggested to explain why  $k_{SP}$  is higher than 1.



**Figure 1.** Load dependence of the factor  $k_{SP}$  for P91 steel determined from LICON and INTEGRITY projects [24] and IMT Slovenia [23] and IPM Brno creep results [30].

### 1.2 Large deformation effect

Hyde and Sun pointed out that the stationary stage of the SP creep curve is at the tertiary creep stage, rather than at the secondary creep stage. The reason is that the strain already reaches a level of 10-15% at such deflections [26]. Analysis of large deformation of a uniaxial specimen, in which strain rate  $\dot{\epsilon}$  at small strains is governed by the Norton equation, results in

$$\dot{\epsilon} = A[(1 + \epsilon)\sigma]^n, \quad (2)$$

where  $\epsilon$  and  $\sigma$  are engineering strain and engineering stress, respectively,  $A$  is a temperature-dependent factor and  $n$  is an exponent dependent on deformation mechanism.

An idea was put forward that the stress and strain entering into Chakrabarty analysis of membrane stretching are true stress  $\sigma_T$  and true strain  $\epsilon_T$ , whilst these are engineering stress (i.e. the initial stress in constant load creep test)  $\sigma$  and engineering strain  $\epsilon$  in the uniaxial test. Therefore when we compare the creep properties derived from the SPC test and the uniaxial test, the true stress and true strain in small punch test should be converted back to

engineering stress and engineering strain. According to the relation between true stress-strain and engineering stress-strain, we have:

$$\sigma = \sigma_T \exp(-\varepsilon_T). \quad (3)$$

The large deformation effect will give significant influence on the stress dependence of the rupture time. Assuming that for the CoP formula (1) is expressed in terms of the true stress no correction regarding experimental data is necessary. Substitution of the engineering stress  $\sigma$  into the left-hand side of Eq. (1) clearly reveals that:

$$k_{SP} = \exp(\varepsilon_T) = 1 + \varepsilon. \quad (4)$$

That is the reason why  $k_{SP}$  is always greater than 1, and its value depends on the strain  $\varepsilon$  at the minimum strain rate. The bigger the strain  $\varepsilon$ , the larger the value of  $k_{SP}$ . The large deformation effect can partially explain the difference between the theoretical and the experimental results, however, when the strain  $\varepsilon$  is too big due to large load deflection, Eq. (4) will give over correction.

The Norton constants  $A$  and  $n$  can be determined using the true stress  $\sigma_T$  and the true strain rate  $\dot{\varepsilon}_T$ , or using the engineering stress  $\sigma$  and the engineering strain rate  $\dot{\varepsilon}$ . The obtained results are quite close, but they are not exactly the same. Therefore, the large deformation effect gives a negligible influence on Norton constants.

### 1.3 Strain hardening effect

The effect of strain hardening should also be considered in creep analysis. For FEM analysis, the elastic plastic properties are part of the input data; therefore the strain hardening effect is already included automatically in the creep analysis. However, when the Chakrabarty model is used to derive the stress, the strain hardening effect should be considered, i.e., the stress given by the Chakrabarty model cannot be higher than those resulting from strain hardening law, e.g. given by combination of Hooke and Ramberg-Osgood equation:

$$\sigma = E\varepsilon \quad (\sigma \leq \sigma_y), \quad (5)$$

$$\sigma = K\varepsilon^p \quad (\sigma > \sigma_y), \quad (6)$$

where  $E$  is the elastic modulus and  $K$  and  $p$  are constants. In order to reduce the influence from excessive plastic deformation, Li suggested [31] that the maximum applied load in SPC should be limited: the maximum load  $F$  should not be higher than  $1.891 \times \sigma_y$  for punch radius  $r = 1.25$  mm in order to keep the membrane stress below the yield strength  $\sigma_y$ . This is because, for a uniaxial creep test, the applied stress is never higher than the yield strength.

### 1.4 Pre-strain effect

Hyde and Sun [26] insist that the excessive initial plastic deformation certainly influences the creep behavior. The evidence is that, even using the uniaxial data as input to the finite element analysis, the calculated deflection vs. time curve still does not coincide with the measured SPC curve. The importance of the effect drew the attention of Ule et al. [32]. They proposed and realized testing small punch specimens of a sombrero shape to avoid initial deformation after loading flat disc specimens. Recently, Cortellino et al. [29] have published their experimental and numerical results and prove that, the effect of pre-straining really exists and should be considered in the interpretation of creep properties.

## 2. Correlation of small punch and uniaxial data

The formula in the CoP is based on the Chakrabarty model. Although it is quite simple, it is obviously not sufficient to predict the creep behavior correctly. On the other hand, the large deformation effect, the strain hardening effect and the pre-strain effect are too complicated for engineering practice. A concept of "Fracture-based correlation" was put forward by Dobeš and Dymáček [33,34], the equivalent stress  $\sigma$  is derived using the rupture

time in SPC with the uni-axial data. In this paper, the “Fracture-based correlation” is further improved, not only to estimate the rupture time, but also to estimate the minimum strain rate. This new methodology is called the “SPC-curve-based approach”. This approach is fully based on experimental tests data, no model or assumption is adopted. Thus all the effects mentioned above are already included. In addition, this approach delivers better prediction than the formula in CoP or the Chakrabarty model. Furthermore, it is very simple and user-friendly.

### 2.1 The “SPC-curve-based approach”

In order to predict the yield strength and the ultimate tensile stress from small punch tests at constant deflection rate, Purmenský and Matocha [35] proposed a correlation approach. They built up a data pool that includes both small punch and uniaxial tests data, and found an optimal parameter in small punch tests relative to the uniaxial quantities.

A similar approach can be applied to SPC analysis. However, the SPC analysis is more complicated than that in a constant deflection rate test. As in SPC, both the creep rupture time and the Norton creep law should be dealt with.

The basic idea of the “SPC-curve-based approach” is that the equivalent stress  $\sigma$  in SPC test can be estimated using the rupture time comparable with the uniaxial data, thus the ratio  $\Psi = F/\sigma$  is obtained. Using the obtained equivalent stress  $\sigma$  the minimum strain rate can be also derived from the uniaxial data. The resulting ratio  $\Psi$  and the minimum strain rate are summarized in a sufficiently large data pool, from which empirical formulas of the ratio  $\Psi$  and the relation between the minimum deflection rate  $\dot{u}_{\min}$  and the minimum strain rate can be established with an optimal parameter.

### 2.2 The data pool

The test data pool contains 97 uni-axial tests and 159 SPC tests, covering temperatures from 550 °C to 700 °C, loads from 300 N to 900 N. The current materials, both new and exposed, are mainly low alloy steels and 9Cr steels, such as 14MoV63, X20CrMoV121, P91, P92 and Eurofer'97. A single example of austenitic steels, namely 316 L steel, is also included in the data pool. The contents and the data sources of the data pool are listed in Table 1. The test data were treated by Matlab procedure described in [38].

**Table 1.** The contents and data sources of the data pool.

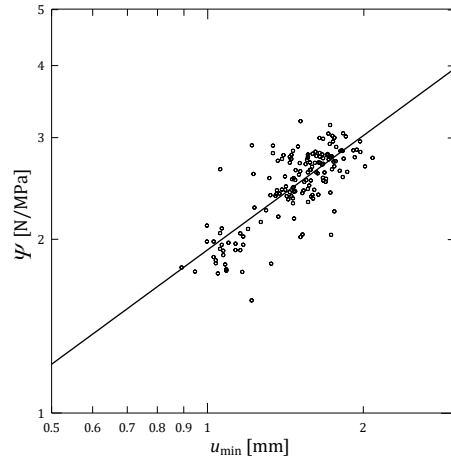
No.	Material name	Temperature (°C)	Number of uni-axial tests	Number of SPC tests	Data source
1	14MoV63	550	4	2	IPM, IMT [4]
2	14MoV63	600	4	37	IPM,IMT [4]
3	14MoV63	650	4	2	IPM,IMT [4]
4	316L	700	4	5	JRC to be published
5	Eurofer'97	550	3	6	IPM [33]
6	Eurofer'97	600	4	7	IPM [33]
7	Eurofer'97	650	5	7	IPM [33]
8	MARBN-NPM1	600	5	4	IPM to be published
9	P22	600	7	15	IPM [36]
10	P91	620	4	8	IMT [23]
11	P91	550	5	6	IPM [30]
12	P91	575	6	6	IPM [30]
13	P91	600	6	7	IPM [30]
14	P92NT	600	5	7	IPM [34]
15	P92	600	4	5	JRC, IPM [34]
16	P92	600	4	5	IPM [34]
17	P92	625	3	5	JRC, IPM [34]
18	P92	650	2	5	JRC, IPM [34]
19	P92	650	4	5	IPM [34]
20	X20CrMoV121	550	4	3	IPM, IMT [37]
21	X20CrMoV121	600	4	6	IPM, IMT [37]
23	12.5Cr-4Ni-Mo	600	6	6	IPM (to be published)

### 2.3 Determination of equivalent stress

The deflection  $u_{\min}$  at the minimum deflection rate  $\dot{u}_{\min}$  is found to be the optimal parameter for the ratio  $\Psi$ . The acquired data pairs  $(F/\sigma, u_{\min})$  are then fitted to the following empirical formula (Fig. 2)

$$\Psi = \frac{F}{\sigma} = B \cdot u_{\min}^m \quad (\text{N/MPa}). \quad (7)$$

The best fit is found at  $B = 1.9204$  and  $m = 0.6530$ .



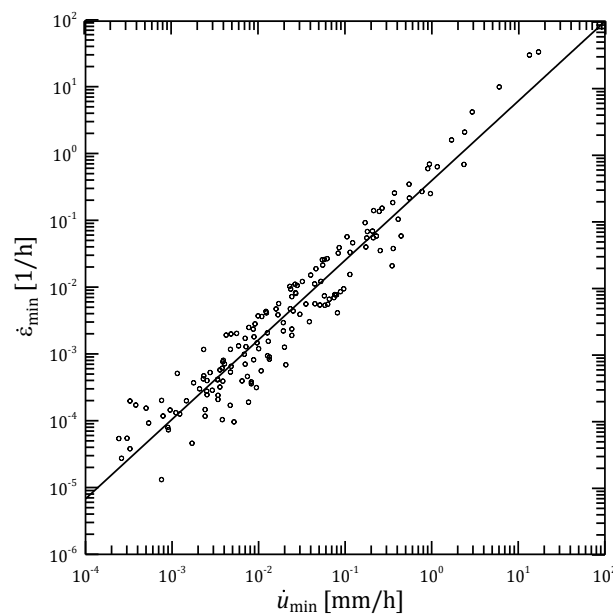
**Figure 2.** Relation between  $\Psi$  and the deflection  $u_{\min}$  at the minimum deflection rate  $\dot{u}_{\min}$ .

### 2.4 Determination of the minimum strain rate

The derived minimum strain rates are also summarized in the same data pool. An empirical relation between the minimum deflection rate  $\dot{u}_{\min}$  and the minimum strain rate is established and expressed as follows (see Fig. 3).

$$\dot{\epsilon}_{\min} = C \cdot \dot{u}_{\min}^q \quad (1/h), \quad (8)$$

where the constants  $C = 3.9220$  and  $q = 1.1907$ .



**Figure 3** Relation between the minimum deflection rate  $\dot{u}_{\min}$  and the minimum strain rate  $\dot{\epsilon}_{\min}$ .

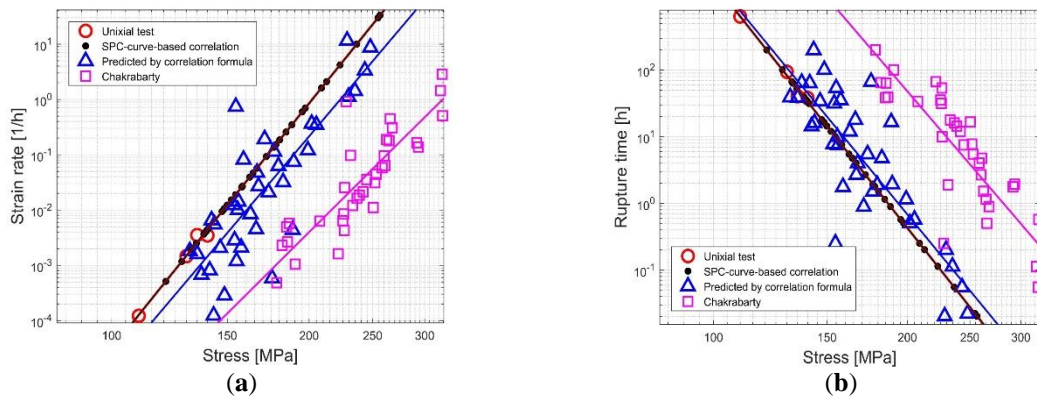
### 3. Prediction of creep properties using “SPC-curve-based approach”

The procedure using the “SPC-curve-based approach” is described as follows. Carry out SPC test. For given load  $F$ , measure the rupture time  $t_r$ , the minimum deflection rate  $\dot{u}_{\min}$ , and the deflection  $u_{\min}$  at the minimum deflection rate  $\dot{u}_{\min}$ . Using the deflection  $u_{\min}$  at the minimum deflection rate  $\dot{u}_{\min}$ , determine the ratio  $\Psi = F/\sigma$  from Eq. (7), and consequently the equivalent stress  $\sigma$  is also obtained. Using the minimum deflection rate  $\dot{u}_{\min}$ , determine the minimum strain rate  $\dot{\epsilon}_{\min}$  from Eq. (8). With the equivalent stress  $\sigma$ , the rupture time  $t_r$ , and the minimum strain rate  $\dot{\epsilon}_{\min}$  known, the rupture time vs. stress dependence and the Norton creep law are obtained.

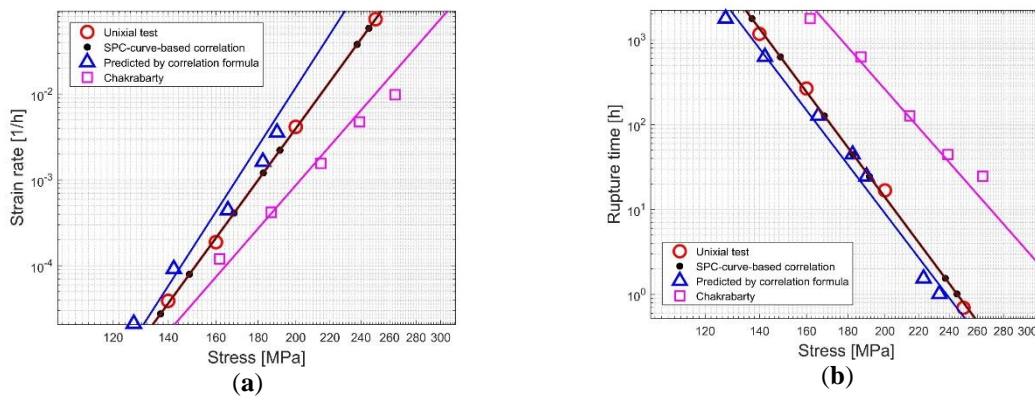
### 4. Verification and examples

The best method for verification is to compare the prediction results directly with the uni-axial tests. The verification has been carried out for each test set during building up the data pool. Herewith some examples are shown below for predictions of the rupture time and the minimum strain rate. The prediction of Chakrabarty model is also attached. Obviously, the present approach gives much better prediction than the Chakrabarty model.

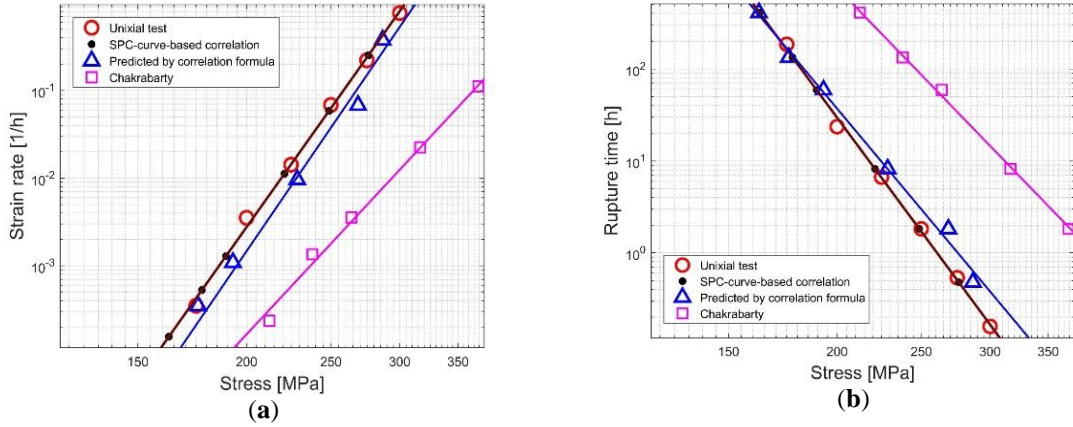
In Figs. 4-9, the open circles and the fit are the uniaxial data; for the black points and the fit, the equivalent stress  $\sigma$  are estimated using the rupture time in SPC test to compare the uniaxial data, then using the obtained equivalent stress  $\sigma$  to calculate the minimum strain rate in SPC from the uniaxial data, thus the two fits always overlap; the open triangles are derived from the empirical formulas Eqs. (7) or (8); the open squares are derived from Chakrabarty model.



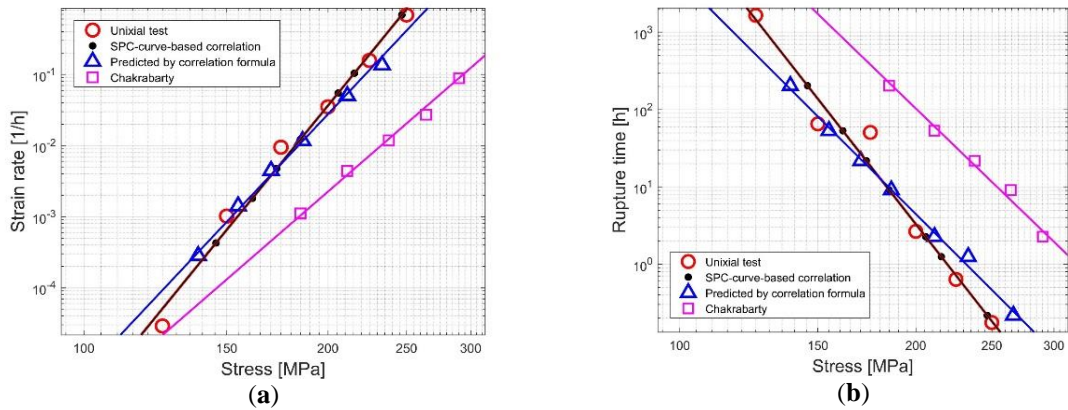
**Figure 4.** Comparison of 14MoV63 at 600 °C uni-axial data with prediction methods (a) Norton creep law; (b) Rupture time.



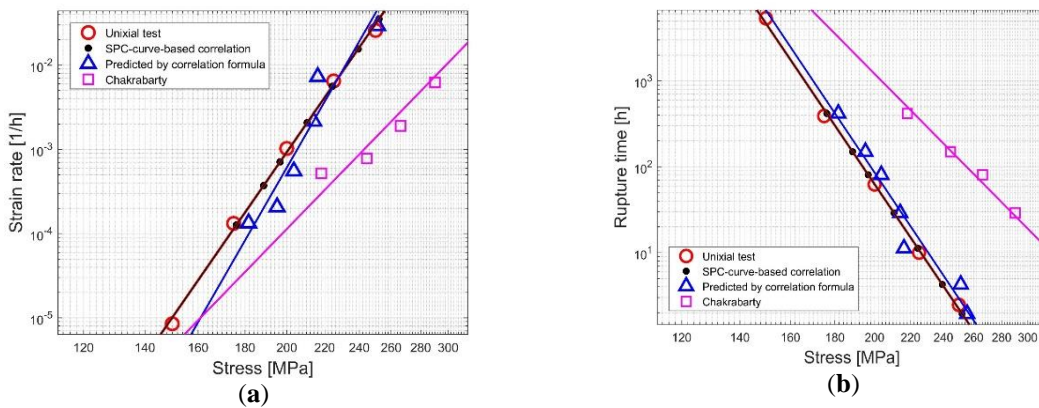
**Figure 5.** Comparison of Eurofer'97 at 600 °C uni-axial data with prediction methods (a) Norton creep law; (b) Rupture time.



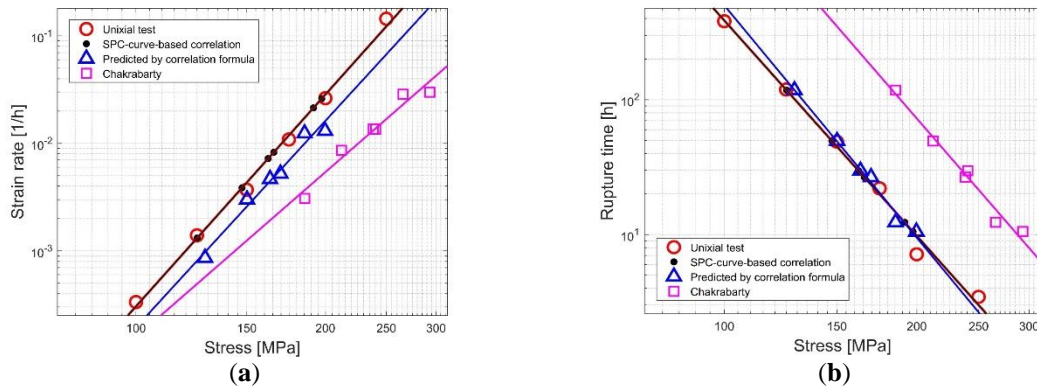
**Figure 6.** Comparison of P91 at 575 °C uniaxial data with prediction methods (a) Norton creep law; (b) Rupture time.



**Figure 7.** Comparison of P91 at 600 °C uniaxial data with prediction methods (a) Norton creep law; (b) Rupture time.



**Figure 8.** Comparison of P92NT at 600 °C uniaxial data with prediction methods (a) Norton creep law; (b) Rupture time.



**Figure 9.** Comparison of 12.5Cr-4Ni-Mo steel at 600 °C uni-axial data with prediction methods (a) Norton creep law; (b) Rupture time.

## 5. Conclusions

The Chakrabarty model [21, 23] has been introduced in the European CoP to estimate the creep load setting. However, it is not sufficient for the prediction of creep properties from SPC tests. This is because the complicity of the SPC problem, as too many non-linearities are involved. Efforts have been made by considering different effects; however none of them is commonly accepted yet.

This paper puts forward a new methodology directly using experimental data. This is because the experimental data contains all effects, no theoretical assumption is needed.

Empirical formulas are given to estimate the equivalent stress and the minimum strain rate, thus creep properties can be predicted using the measured SPC data.

Verification has been carried out and shows that the predictions by the empirical formulas are in good agreement with the uniaxial data, and much better than those predicted by Chakrabarty model.

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## References

1. Manahan, M.P.; Argon, A.S.; Harling O.K., The development of a miniaturized disk bend test for the determination postirradiation mechanical properties. *J Nucl Mater* **1981**, 103&104, pp.1545-1550, DOI: 10.1016/0022-3115(82)90820-0.
1. Baik J.M.; Kameda J.; Buck O. Small punch test evaluation of intergranular embrittlement of an alloy steel. *Scripta Metall* **1983**, 17, pp. 1443-1447, DOI: 10.1016/0036-9748(83)90373-3.
2. Parker J.D.; James J.D. Disc-bend Creep Deformation Behaviour of 1/2Cr1/2Mo1/4V Low Alloy Steel. Proceedings of the Fifth International Conference on the Creep and Fracture of Engineering Materials and Structures, The Institute of Metals, London, 1993, pp. 651-660.
3. Ule B.; Šustar T.; Dobeš F.; Milička K.; Bicego V.; Tettamanti S.; Maile K.; Schwarzkopf C.; Whelan M.P.; Kozłowski R.H.; Klaput J. Small punch test method assessment for the determination of the residual creep life of service exposed components: outcomes from an interlaboratory exercise. *Nucl Eng Des* **1999**, 192, pp. 1–11, DOI: 10.1016/S0029-5493(99)00039-4.
4. CEN/WS CWA 15627 Workshop agreement: Small Punch Test Method for Metallic Materials. Part 1: A Code of Practice for Small Punch Testing at Elevated Temperatures. Report No. CEN/WS 21, European Committee for Standardization, 2007 Brussels
5. Ma Y.W.; Shim S.; Yoon K.B. Assessment of power law creep constants of Gr91 steel using small punch creep tests. *Fatigue Fract Eng M* **2009**, 32, pp. 951–960, DOI: 10.1111/j.1460-2695.2009.01394.x.

6. Rouse J.P.; Cortellino F.; Sun W.; Hyde T.H.; Shingledecker J. Small punch creep testing: review on modelling and data interpretation. *Mater Sci Tech-Lond* **2013**, 29: 1328-1345, DOI: 10.1179/1743284713Y.0000000278.
7. Rodríguez C.; Cárdenas E.; Belzunce F.J.; Betegón C. Fracture characterization of steels by means of the small punch test. *Exp Mech* **2013**, 53, pp. 385–392, DOI: 10.1007/s11340-012-9637-x.
8. Alegre J.M.; Cuesta I.I.; Lorenzo M. An extension of the Monkman-Grant model for the prediction of the creep rupture time using small punch tests. *Exp Mech* **2014** 54, pp.1441–1451, DOI: 10.1007/s11340-014-9927-6.
9. Lee T.; Ibupoto F.A.; Lee J.H.; Kim B.J.; Kim M.K. A direct methodology for small punch creep test. *Exp Mech* **2016**, 56, pp. 395–405, DOI: 10.1007/s11340-015-0108-z.
10. Nakata T.; Komazaki S.; Kohno Y.; Tanigawa H. Effects of geometry and dimension of specimen and rig on small punch creep property. *Exp Mech* **2017**, 57, pp. 487–494, DOI: 10.1007/s11340-016-0250-2.
11. Andrés D.; Lacalle R., Álvarez J.A. Creep property evaluation of light alloys by means of the Small Punch test: creep master curves. *Mater Des* **2016**, 96, pp.122–130, DOI: 10.1016/j.matdes.2016.02.023.
12. Holmström S.; Auerkari P.; Hurst R.; Blagoeva D. Using small punch test data to determine creep strain and strength reduction properties for heat affected zones. *Mater Sci Tech-Lond* **2014**, 30, pp. 63-66, DOI: 10.1179/1743284713Y.0000000311.
13. García T.E.; Rodríguez C.; Belzunce F.J.; Suárez C. Estimation of the mechanical properties of metallic materials by means of the small punch test. *J Alloy Compd* **2014**, 582, pp. 708–717, DOI: 10.1016/j.jallcom.2013.08.009.
14. Geng J.F.; Cai H.S.; Ma D.F.; Feng X.S.; Guan K.S. Identification of creep parameters of P91 by small punch test. *Appl Mech Mater* **2014**, 529, pp. 439-443, DOI: 10.4028/www.scientific.net/AMM.529.439.
15. Naveena; Komazaki S. Evaluation of creep rupture strength of high nitrogen ferritic heat-resistant steels using small punch creep testing technique. *Mater Sci Eng A* **2016**, 676, pp. 100-108, DOI: 10.1016/j.msea.2016.08.102.
16. Hurst R.C.; Lancaster R.J.; Jeffs S.P.; Bache M.R. The contribution of small punch testing towards the development of materials for aero-engine applications. *Theor Appl Fract Mec* **2016**, 86, pp. 69-77, DOI: 10.1016/j.tafmec.2016.07.013.
17. Dyson C.C.; Sun W.; Hyde C.J.; Brett S.J.; Hyde T.H. Use of small specimen creep data in component life management: a review. *Mater Sci Tech-Lond* **2016**, 32, pp. 1567-1581, DOI: 10.1080/02670836.2015.1132536.
18. Nakata T.; Komazaki S.; Kohno Y.; Tanigawa H. Development of a small punch testing method to evaluate the creep property of high Cr ferritic steel: Part I – effect of atmosphere on creep deformation behaviour. *Mater Sci Eng A* **2016**, 666, pp. 54–60, DOI: 10.1016/j.msea.2016.03.100.
19. Ortiz-Mariscal A.; Saucedo-Muñoz M.L.; Naveena; Komazaki S. Application of small punch creep testing for evaluation of creep properties of as received and artificially aged 5Cr-0.5Mo steel. *Mater Sci Eng A* **2018**, 709, pp. 322-329, DOI: 10.1016/j.msea.2017.10.060.
20. Chakrabarty J. A theory of stretch forming over hemispherical punch heads. *Int J Mech Sci* **1970**, 12, pp. 315-325, DOI: 10.1016/0020-7403(70)90085-8.
21. Yang Z.; Wang Z. Relationship between strain and central deflection in small punch creep specimens. *Int J Pres Ves Pip* **2003**, 80, pp. 397-404, DOI: 10.1016/S0308-0161(03)00069-3.
22. Li Y.; Sturm R. Determination of creep properties from small punch test. In: Proceedings of the ASME Pressure Vessels & Piping Conference PVP 2008, Chicago, **2008**, Vol. 3, pp. 739-750, DOI: 10.1115/PVP2008-61437.
23. Blagoeva D. Development of a residual lifetime prediction methodology for creep and fracture behaviour of ferritic-martensitic steels using small punch testing technique. Dissertation, Università di Pisa, Pisa, **2009**.
24. Nonaka I.; Kanaya A.; Komazaki S.; Kobayashi K. Standardization of test method for small punch creep testing in Japan. *Metallurgical J* **2010**, 63, pp.12-18.
25. Hyde T.; Sun W. Interpretation of small punch creep test data for ductile materials. *Metallurgical J* **2010**, 63, pp. 25-33
26. Wen Ch.; Xu T.; Guan K. Correlation factor study of small punch creep test and its life prediction. *Materials* **2016**, 9, 796, DOI: 10.3390/ma9100796.
27. Yang S.; Ling X.; Zheng Y. Creep behaviors evaluation of Incoloy800H by small punch creep test. *Mater. Sci. Eng. A* **2017**, 685, pp. 1–6, DOI: 10.1016/j.msea.2016.12.092.

28. Cortellino F.; Rouse J.P.; Cacciapuoti B.; Sun W.; Hyde T.H. Experimental and numerical analysis of initial plasticity in P91 steel small punch creep samples. *Mater Sci Tech-Lond* **2017**, 57, pp. 1193–1212, DOI: 10.1007/s11340-017-0296-9.
29. Milička K.; Dobeš F. Small punch testing of P91 steel. *Int J Pres Ves Pip*, **2006**, 83, pp. 625–634, DOI: 10.1016/j.ijpvp.2006.07.009.
30. Li Y.; Stevens P.; Geng J.; Ma D.; Xu L. Determination of creep properties from small punch test with reverse algorithm. *Key Eng Mat*, **2017**, 734, pp. 212-236, DOI: 10.4028/www.scientific.net/kem.734.212.
31. Ule B.; Šuštar T. The effect of initial hot plastic deformation on creep behaviour of 12 Cr steel specimens in small punch tests. *Mater High Temp* **2001**, 18, pp. 163-170.
32. Dobeš F.; Dymáček P. Fracture-based correlation of uniaxial and small punch creep data. *Theor Appl Fract Mec* **2016**, 86, pp. 34-38, DOI: 10.1016/j.tafmec.2016.08.020.
33. Dymáček P. Recent developments in small punch testing: Applications at elevated temperatures. *Theor Appl Fract Mec* **2016**, 86, pp. 25-33, DOI: 10.1016/j.tafmec.2016.09.013.
34. Purmanský J.; Matocha K. Testing of small specimens in physical metallurgy. In: Prnka T (ed) Proceedings of the 10th International Metallurgical Conference METAL 2001, TANGER, Ostrava, Czech Republic, 2001 pp. 70/1–70/13.
35. Dymáček P.; Milička K. Small punch testing and its numerical simulations under constant deflection force conditions. *Strength Mater* **2008**, 40, pp. 24-27, DOI: 10.1007/s11223-008-0007-y.
36. Dobeš F.; Milička K.; Ule B.; Šuštar T.; Bicego V.; Tettamanti S.; Kozłowski R.H.; Klaput J.; Whelan M.P.; Maile K.; Schwarzkopf C. Miniaturized disk-bend creep test of heat-resistant steels at elevated temperatures. *Eng Mech* **1998**, 5, pp. 157-160.
37. Li Y.; Stevens P.; Dymáček P.; Dobeš F. Procedure of SPC data treatment for correlation with uniaxial tests SSTT2018, Swansea 2018 (submitted).