Force-to-Stress Conversion Methods in Small Punch Testing Exemplified by Creep Results of Fe-Al Alloy with Chromium and Cerium Additions

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Abstract. Application of the small punch test in technical practice is critically dependent on the existence of reliable methods for conversion of data measured by means of such a biaxial test to equivalent quantities of uniaxial tests. In the paper, various methods for recalculation of force in small punch test to stress in conventional creep test are investigated. The methods include: (i) classical “CEN Workshop Agreement” model, (ii) empirical “force to stress conversion” method, (iii) modified Chakrabarty method and (iv) “constant deflection rate” method. The methods are examined using the data obtained by testing Fe-Al based alloy with additions of chromium and cerium. The tested alloy enables verification of conversion methods for different crystallographic lattices, namely D0₃ at lower temperatures and B2 at elevated temperatures.

1 Introduction
An attractive possibility for estimation of the residual lifetime of facilities operating at elevated temperatures includes testing of miniaturized discs detracted non-invasively from the surface of construction parts, i.e., small punch (SP) testing [1-5]. An important prerequisite for practical application of such testing is establishing reliable correlative means for comparison of force in SP test and stress in conventional creep test. A range of force-to-stress conversion methodologies were recently compared in connection with the preparation of new European standard for small punch testing [6]. In the present contribution we would like to verify the methodologies using data obtained in research of Fe-Al-based alloy. Furthermore, another method is proposed that starts from results of SP tests at constant rate of deflection.

2 Material and experimental technique
The alloy containing 28.4 % Al, 2.6 % Cr, 0.02 % Ce and 0.16 % C (at. %, Fe balanced) was prepared by vacuum melting, casting in an argon atmosphere and rolling of the original sheet (thickness 40 mm) to the final one (13 mm) at 1100 °C. Details of its preparation and final microstructure can be found elsewhere [7]. SP creep tests were performed at temperatures ranging from 500 °C to 800 °C and applied forces from 40 N to 500 N. Specimens of 8 mm in diameter and thickness of 0.500 ± 0.002 mm were used, the geometry of SP setup was as follows: punch radius 1.25 mm, lower die radius 2 mm. The central deflection was measured through the relative motion of the punch. This is in contrast to measurements in ref. [6] where it was done through the movement of a ceramic rod attached to the specimen from the opposite side. Results of SP tests are described in the previous paper [8]. For the
sake of extending the conversion methodology, additional tests at constant deflection rate of 0.0055 mm/s were performed at both room temperature and elevated temperatures. For a direct comparison with uniaxial tests, the results of conventional creep tests in tension - performed on the same sheet are used [9]. In a similar way, results of constant strain rate tests published in conference contribution [10] are also used.

3 SPC conversion methodologies

3.1 Classical “CEN Workshop Agreement” model

In the preliminary European Code of Practice [11], a rough estimate of the relationship between force $F$ in small punch test and stress $\sigma$ in conventional test is made using the Chakrabarty membrane stretch model [12]

$$F / \sigma = 3.332k_{SP}F^{-0.2}R^{1.2}h_0$$

(1)

where $r$ is radius of lower die, $R$ is punch radius and $h_0$ is initial thickness of the disc. $k_{SP}$ is a correlation factor introduced to adjust the theoretical model to the experimental results. The original idea of $k_{SP}$ equal to unity is indefensible of view of available experimental results [13-15]. Comparing force $F$ in our SP tests and stress in uniaxial tests [9] of the same duration, the values of $k_{SP}$ for the present geometry can be found. They are presented in figure 1 as a function of time to rupture. $k_{SP}$ is clearly a function of temperature and time to rupture (i.e., force). A striking difference is evident between values at temperature of 500 °C and at temperatures in the range from 600 to 800 °C. This can be ascribed to difference in crystal lattices: at temperatures above 540 °C, the less-ordered FeAl phase with B2 lattice exists, whereas at lower temperatures the stable compound is ordered Fe$_3$Al with D0$_3$ lattice [16].

![Figure 1. Dependence of ductility parameter $k_{SP}$ on time to rupture at different temperatures.](image)

3.2 Empirical “force to stress conversion” method (EFS)

For the prepared European small punch standard a fully empirical force-to-stress conversion model was chosen as the preferred methodology [6]. It was shown that the force-to-stress ratio is dependent on the value of deflection $u_m$ measured at the location of the minimum deflection rate. The optimized formula is then [6, 15]

$$F / \sigma = 1.9162u_m^{0.6579}.$$ 

(2)
Comparison of the stress dependence of time to rupture measured by uniaxial creep tests (UAC) [9] and the results of small punch creep tests (SPC) dependent on equivalent stress calculated by means of equation (2) is given in figure 2a. The agreement of uniaxial data and recalculated small punch data in the B2 range of temperatures is excellent. On the other hand, the results in D03 range (500 °C) do not match well. This is not surprising because the empirical formula (2) is based entirely on the results of ductile steels while the present alloy is evidently brittle in D03 state.

![Figure 2](image)

**Figure 2.** Dependence of time to rupture in small punch creep tests and uniaxial creep tests on calculated equivalent stress and applied stress, respectively. Equivalent stress calculated using: a) equation (2) and b) equation (3).

### 3.3 Modified Chakrabarty method (MCH)

A linearized version of EFS formula was suggested by Holmström et al. [6] in order to simplify the approach and to open the possibility to account for different types of test set-ups. The MCH optimized force to stress ratio for the standard test set-up is

\[
F / \sigma = 0.6143 + 1.2954 t_m
\]

Comparison of the small punch data, recalculated to equivalent stress using the equation (3), with the results of uniaxial creep tests is given in figure 2b. Similar conclusions can be deduced about the conformity of measured and calculated data as in the foregoing paragraph: The agreement in the B2 range of temperatures is slightly inferior, the results in D03 range do not match well.

### 3.4 Methods based on constant deflection rate tests

In principle, three main different testing modes of small punch can be operated:

- First, Constant Force (CF) is a test in which the punch penetrates under a constant force \( F \) and the time dependence of the deflection is recorded. This test is similar to conventional constant load creep tests.
- Second, the punch penetrates through the disc at a given constant rate of motion and the force \( F \) is measured [17-19]; this test is termed Constant Deflection Rate (CDR) in what follows. It has certain analogy with the conventional tensile test under a constant strain rate. The tests can be used for estimation of yield stress \( \sigma_y \) and ultimate tensile strength \( \sigma_{UTS} \) [20-22].
- Third, the constant deflection mode is the analogy to stress relaxation testing. The deflection of the disc (preferably in conditions of the membrane stretching regime) is held constant and the force relaxes as the elastic strain is replaced by inelastic creep strain [23].
Komazaki [24] recently suggested that the ratio of maximum force in CDR test to ultimate tensile strength can be used as a conversion factor of force in small punch CF tests to stress in uniaxial creep test:

\[ \frac{F}{\sigma} = \frac{F_{\text{max}}}{\sigma_{\text{UTS}}} \]  

(4)

This proposal can be of enormous importance, especially if its validity is demonstrated for room temperature values of \( F_{\text{max}} \) and \( \sigma_{\text{UTS}} \) to conversion of elevated temperature creep data. The application of room temperature data is certainly problematic in the present intermetallic alloy due to existence of different crystal lattices at different test temperatures [16]. That is why the data at specific temperature should be preferred in our investigation: Temperature dependence of \( \sigma_{\text{UTS}} \) was published by Hakl et al. [10]; dependence of force on deflection in CDR tests is illustrated in figure 3.

![Figure 3](image-url)

**Figure 3.** Force vs. deflection curves at various temperatures.

Comparison of small punch data recalculated using the equation (4) and uniaxial creep data is given in figure 4a. The SPC points at 800 °C are not included in the figure because the ultimate tensile strength is not available at this temperature. The agreement of the SPC and UAC points is the worst of all the methods tested in the present investigation. Moreover, the application of the method requires a value of the ultimate tensile strength at a given temperature that is usually not known.

The idea of conversion SPC into UAC data using the results of CDR tests can be modified in the following way. It was shown previously [20-22] that the ultimate tensile strength correlates with the results of CDR tests by means of a simple linear relationship

\[ \sigma_{\text{UTS}} = \beta \frac{F_{\text{max}}}{h_0 u_{\text{max}}} \]  

(5)

where \( h_0 \) is the initial thickness of the disc specimen, \( u_{\text{max}} \) is the deflection corresponding to the maximum force and \( \beta \) is a constant. The conversion factor which follows the idea of equation (4) is then

\[ \frac{F}{\sigma} = \frac{h_0 u_{\text{max}}}{\beta} \]  

(6)
To estimate the conversion factor for a series of SPC tests at given temperature it is necessary to perform only a single CDR test and to determine the value of deflection $u_{\text{max}}$ at the maximum force. The values of the constant $\beta$ found in available studies are reviewed in our previous paper [21]. The value of $\beta = 0.32$ was applied in the present investigation following the recommendation of Komazaki [24]. Comparison of uniaxial and small punch creep data using this value of $\beta$ is given in figure 4b. Because the CDR test at 800 °C is not available, the same value of conversion factor is used as for the temperature of 700 °C. It can be seen that the agreement of UAC and SPC data is very good. Contrary to the above version of CDR-based method (equation 4), the equation (6) may offer a possibility of conversion factor $F/\sigma$ dependent on the force applied in the small punch creep test. This can be realized either through a series of CDR tests at different deflection rates or by refining the equation (5). The tests to confirm the method for heat-resistant steels are in progress.

As can be seen in Fig. 3, several force drops are observed at the temperature of 500 °C. The deflection at the maximum observed force was used as the input in eq. 6. It remains a matter of discussion whether the deflection at the first force drop is not more suitable for the conversion. This would increase the equivalent stress by a factor of two and may improve the fit of very short-term tests that probably cracked at loading. Apparently, the conversion of SPC data of brittle D03 phase requires additional attention and it is beyond the scope of the present contribution. The fractographs of ruptured SP specimens are illustrated in our previous paper [8].

4 Conclusions

Various methods for conversion of force in small punch test to equivalent stress in conventional uniaxial creep tests are compared. The problems emerge in the temperature range of the existence of D0$_3$ lattice. New method based on estimation of deflection corresponding to maximum force in constant deflection rate test is suggested as a potential route for considering the ductility of tested material.

![Figure 4](image-url)

**Figure 4.** Dependence of time to rupture in small punch creep tests and uniaxial creep tests on calculated equivalent stress and applied stress, respectively. Equivalent stress calculated using: a) equation (4) and b) equation (6).
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