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Test methodologies for determining high temperature material properties of thin walled tubes

EERA JPNM Pilot project TASTE

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Foreword

This report is the final report of the EERA JPNM pilot project "Testing and ASsessment methodologies for material Characterization of thin-walled cladding TubEs" (TASTE).

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Abstract

This report presents briefly the test methods used, within the in the EERA JPNM Pilot Project TASTE, for defining the tensile and creep material properties relevant to the integrity of nuclear fuel claddings. These properties are challenging to extract from thin walled tubes since the standard test methods use specimens that require minimum material thicknesses in the order of 10 mm or more. In contrast the thin walled material properties are acquired through a number of testing techniques and evaluation methodologies suitable for the thin walled product form. In this report the different test methods and their data assessment requirements are briefly described. The test methods evaluated here comprise sub-size (curved specimen) tensile testing (ST) of the cladding tube, micro specimen (dog-bone) tensile testing (MT), Small Punch testing (SP), Segmented Expanding Cone Mandrel tests (SCM), ring tension (RT) and ring compression (RC) tests and internal pressure testing (IP).

Introduction

The main objective of this report is to provide the background and assessment methodologies for classical and more recent test types that can be used for determining material properties of thin walled tubes. The TASTE project is an EERA JPNM pilot project that has been performed fully in-kind. The final target of the TASTE project is to recommend an "optimal" set of tools for a comprehensive material property determination. These tools are then used to extracting and estimate the key material properties for the TASTE round robin exercise on 15-15Ti fuel claddings. The properties sought are: high temperature tensile properties, creep strain, creep rupture properties and material ductility.

Currently there is no standard for thin-walled cladding tube material testing but a number of test types are naturally in use for validating design criteria for material behaviour. There are also some new test methods proposed. The different test types and methods are in nature complementary and no method seems to fulfil all features and requirements to extract standard size material properties.

Models and methods

In this report the test methods and assessment procedures covered in the TASTE project are defined and discussed. The actual test results acquired in TASTE, for the titanium stabilized DIN 1.4970 (15-15Ti) stainless steel, will be reported in the final test report. The main test material in TASTE is the nuclear-grade cladding tubes manufactured at Sandvik on behalf of SCK•CEN. The materials specifications include requirements on mechanical properties such as yield strength, tensile strength and elongation at rupture. The test methods studied in the round-robin and the laboratories that contribute to the specific test methods are listed in Table 1. The tests comprise of room temperature and high temperature tests up to 800°C.

Table 1. Test methods and test laboratories in the TASTE project

Method (designation)	Laboratories	Note
Sub-size tensile tests on tube segments (ST)	CIEMAT, HZDR, SCK-CEN	
Micro tensile and creep test (MT, MC)	KIT	Miniature dog-bone specimen
Ring Tension testing (RT)	INR	
Segmented expanding cone mandrel test (SCM)	JRC	
Small Punch test – tensile (SPT)	HZDR, CIEMAT, ENEA, JRC	New test standard under development
Small Punch test – creep (SPC)	JRC	New test standard under development
Ring Compression testing (RC)	ENEA, JRC, CVR	
Internal Pressure testing (IP)	VTT	Burst and axial stress controlled options

The studied features of each test type are:

- Amount of material needed
- Test simplicity
- Specimen preparation
- Possibility for controlled load and displacement
- Hot-cell applicability
- Applicability for testing in corrosive loops
- Biaxiality, controlled or imposed
- Strain rate sensitivity
- Simplicity of material property extraction / evaluation

Tensile properties:

The tensile properties that are estimated with the non-standard test samples and test techniques are compared to values acquired by the standard testing where possible. The standard for tensile properties is for room temperature ISO 6892-1 [2] and for elevated

temperatures ISO 6892-2 [3]. The targeted properties are; the ultimate tensile strength R_m, the yield stress R_{p02} and the fracture elongation ε_f (%).

Sub-sized tensile tests on tube segments (ST)

The sub-sized tensile specimen (ST) test is used for determining the axial (tensile) properties of the thin walled tube. The tensile specimens can be extracted from cladding tubes, for instance by electrical discharging machining (EDM) as shown in Figure 1. Special gripping tools have to be manufactured to ensure that the loading axis is straight with minimum bending.

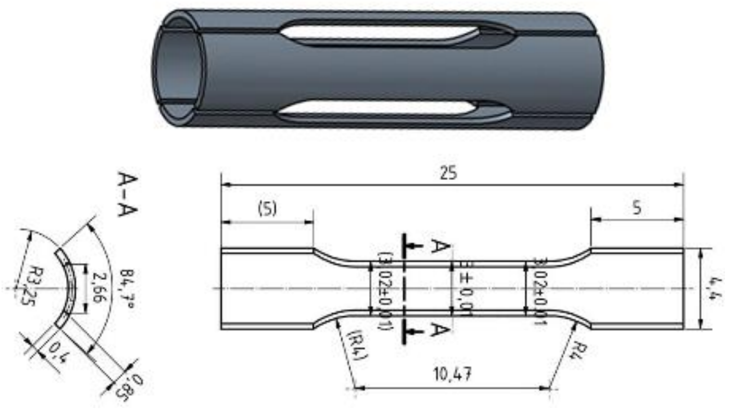


Figure 1. Sub-sized uniaxial specimen manufactured from a cladding tube [4].

The test is usually performed on a general purpose testing machine at a specified constant deflection rate throughout the tests or first at a slower rate until yield and then at an increased rate until failure as is allowed for full size specimen tests in ISO 6892:2 for elevated temperatures.

The deflection-load curves acquired from the tests can be transformed to engineering stress-strain curves by dividing the load by the initial area of the cross section of the gauge length;

$$\sigma = \frac{F}{A_0} \qquad (1)$$

where F is the force, A_0 is the area of the thinned sections of the tube section. The calculated strain is extracted from the measured deflection as;

$$\varepsilon = \frac{L - L_0}{L_0} \qquad (2)$$

where L_0 is the original gauge length of the specimen.

The maximum stress on the stress-strain curve is the ultimate tensile strength R_m. The yield stress R_{p02} is acquired by offsetting the linear fit (passing through origin) line to the pre-defined (here 0.2%) strain and reading the stress at the location of intersection between the stress-strain curve and the line as shown in Figure 2.

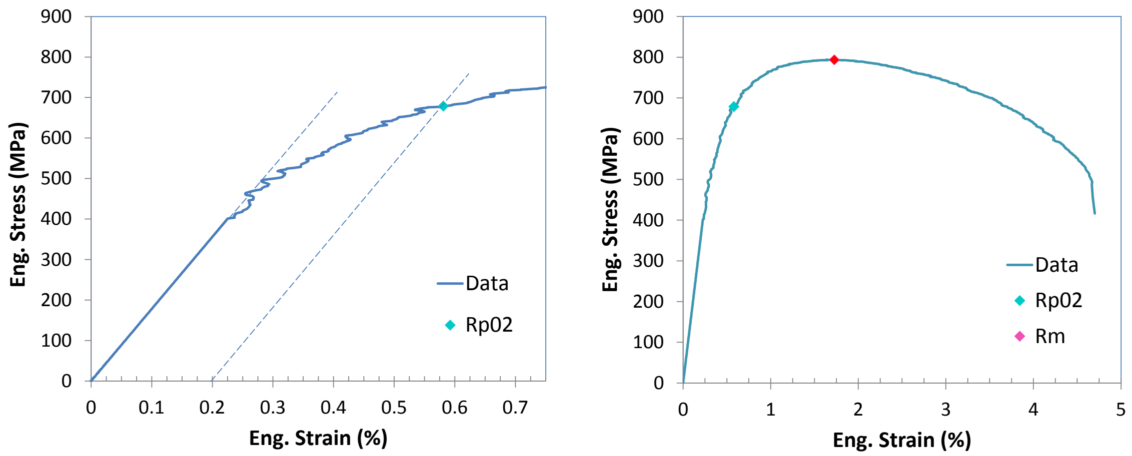


Figure 2. Stress-Strain curve of uniaxial tensile test on curved tube specimen [4]

This test is considered to give the best estimate of the axial material properties of the cladding tube since it is as close to a "standard" tensile test as possible.

The test features for this test type are estimated as:

• Material needed	16 specimen / 10 cm (as in Figure 1)
• Test simplicity	Simple
• Specimen preparation	EDM cut (irradiation problematic?)
• Controlled load and displacement	YES, same as standard tensile
• Hot-cell applicability	Possible
• Testing in corrosive loops	Possible
• Biaxiality, controlled or imposed	Not applicable
• Strain rate sensitivity	Same as for standard tensile test
• Simplicity of assessment	Simple

The Micro tensile test (MT)

With the micro-sized tensile test (MT) specimen can be extracted in both the axial (tensile) and the hoop direction of the thin walled tube. The tensile specimens can for instance be manufactured by micro electrical discharging machining (μEDM) and polishing.

The specimen size can naturally be optimized to suit the thin walled tube (TASTE: Gauge length 0.8 mm and cross section 0.3x0.2 mm). Special gripping tools, high sensitivity loading cells, rigorous specimen alignment procedures and optical displacement measurement have to be used to ensure that the load-deflection curve becomes repeatable and that representative estimates for the tensile properties can be acquired. The specimen and a generalized test setup are shown in Figure 3.

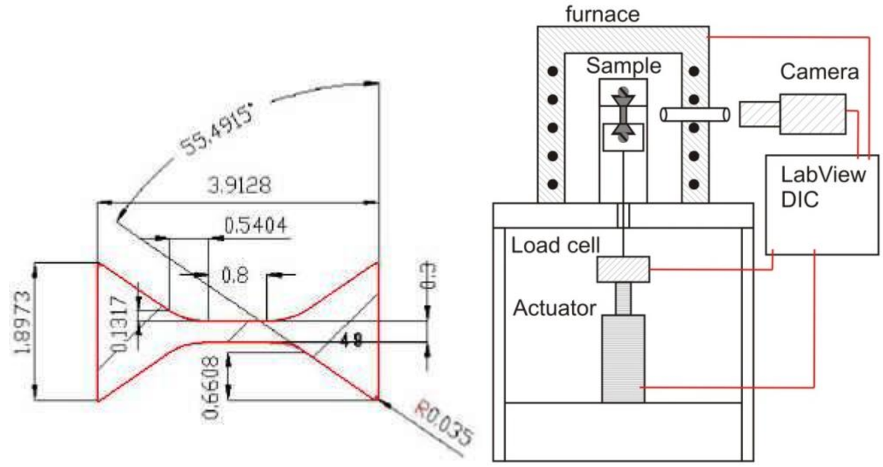


Figure 3. Micro-sized uniaxial specimen manufactured from a cladding tube A) and test set-up B).

The translation of the load-deflection to stress-strain curve is done as for the sub-sized tensile tests (Equations 1 and 2.). Two typical stress-strain curves conducted at room temperature are shown in Figure 4.

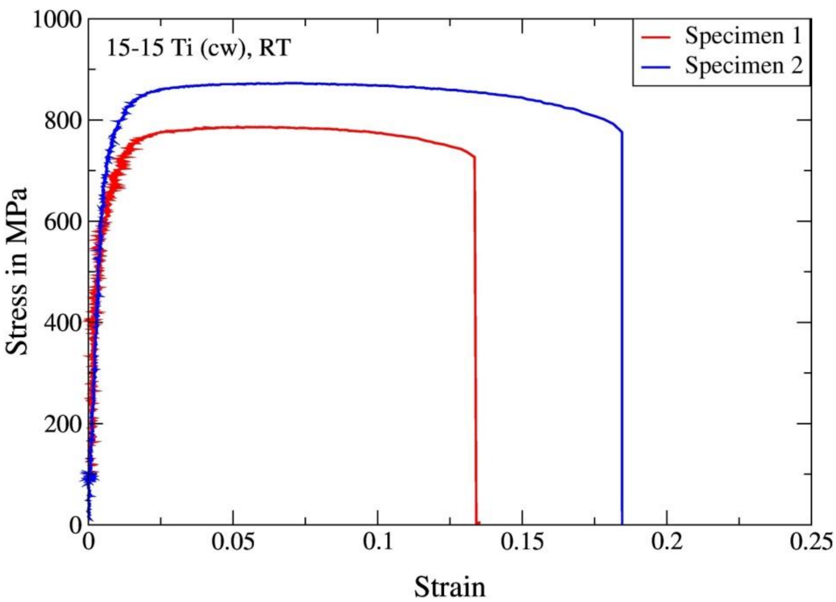


Figure 4. Stress-strain curves from micro specimen room temperature tests.

The determination of both axial and hoop properties can be performed due to the small specimen size.

The test features for this test type are estimated as:

- Material needed — Minimal, large number of specimens
- Test simplicity — Difficult (miniature specimen)
- Specimen preparation — Difficult (μEDM machining)
- Controlled load and displacement — Same as standard tensile tests

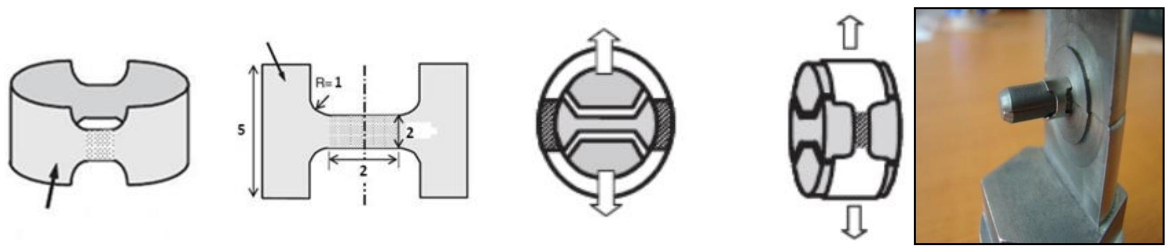
- Hot-cell applicability — Difficult
- Testing in corrosive loops — Difficult
- Biaxiality, controlled or imposed — Not applicable
- Strain rate sensitivity — Same as for standard tensile tests
- Simplicity of assessment — Simple

Ring Tension test (RT)

The ring tension (RT) test is a test for determining material properties in the hoop direction and can be compared to internal pressure (burst) test results. The hoop direction properties are especially needed for tubes made of material with known anisotropic properties or when anisotropy is expected from the fabrication process.

Both tensile and creep testing can be performed with ring specimen, though in TASTE only the tensile property evaluation was performed.

The RT tests are performed by applying a tensile force to the inside of a ring specimen (see Figure 5 A and B) the ring, perpendicular to the axial tube.



A B C

Figure 5. The specimen A), recommended sample mandrels B) and simplified test setup C) [5].

The main shortcomings of this test are the bending deformation due to specimen curvilinear shape and the impact of friction between inserts and test material. The test setup shown in Figure 5-C was used in the TASTE round-robin exercise.

To minimize the friction coefficient between the outer surface of the half cylinders and the inner surface of the specimen lubrication such as vacuum grease or Teflon can be applied. The resulting friction coefficient and the impact of the bending on the measured load-deflection curve has to be calibrated against a reference material with known material properties.

The advantages of the RT tests are the small amount of material needed, the easy specimen preparation and the simple test procedure.

The typical ring tension test curve, i.e. force-deflection curve is nearly identical to the one obtained from uniaxial test specimen (although it is includes bending and friction effects). The test is performed as the uniaxial tensile test with a specified deflection rate (in TASTE 1 mm/min).

In the most basic assessment for determining the hoop direction tensile properties the force-deflection curve is translated into a stress-strain curve in the same way as for uniaxial test samples. The applied force is translated to engineering stress by dividing by the sum of the initial areas of the waist sections of the ring ($2 \cdot A_0$);

$$\sigma = \frac{F}{2A_0}$$

where F is the force, $2A_0$ is the area of both thinned sections (gauge length) of the ring sample. In this simplified assessment the calculated stress does not take into account the bending, stress redistribution and friction.

Also for the calculated strain no corrections for bending are applied. The calculated strain is extracted from the stroke L (deflection) as;

$$\varepsilon = \frac{L - L_0}{L_0}$$

where L_0 is the original parallel length of the waist part of the ring.

The tensile strength and the yield stress are extracted as for uniaxial tests, R_m from the maximum force and R_{p02} by the offset method described in Figure 2 for sub-sized tensile test.

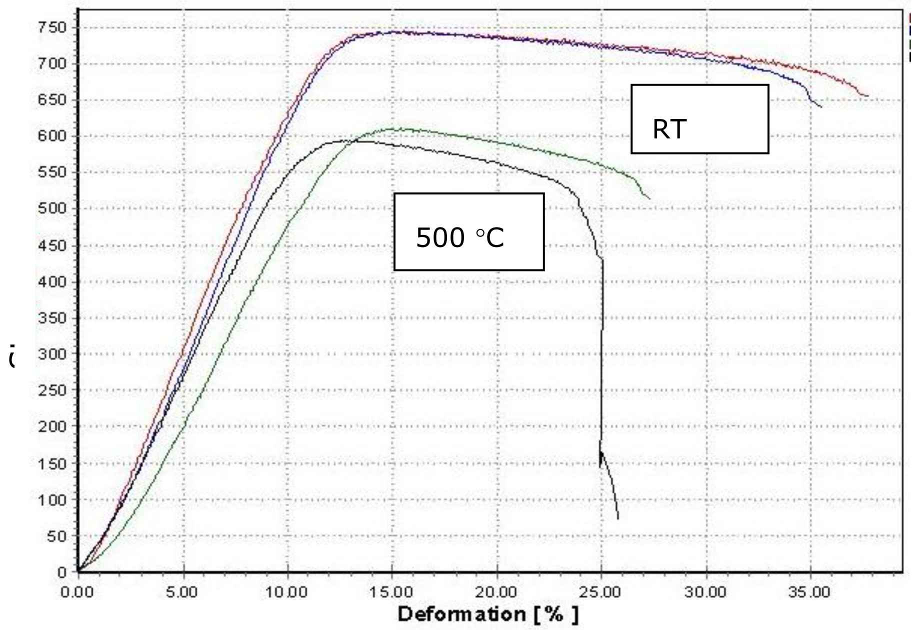


Figure 6. Typical ring tension testing stress-strain curves (15-15Ti at RT and 500°C).

Finite Element Modelling is required to improve the estimates of tensile strength and yield stress by taking bending and friction into account.

The main disadvantage of this test methodology is the impact of bending and friction.

The test features for this test type are estimated as:

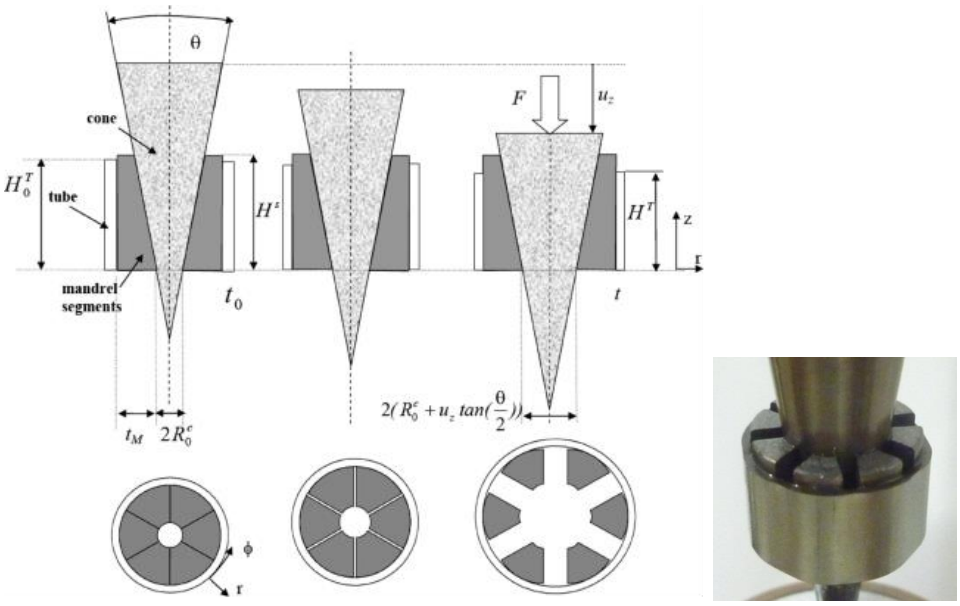
- Material needed — 20 specimen / 10 cm (5 mm rings)
- Test simplicity — Simple
- Specimen preparation — Medium, EDM waisted tube ring
- Controlled load and displacement — Same as for standard tensile test
- Hot-cell applicability — Possible
- Testing in corrosive loops — Possible
- Biaxiality, controlled or imposed — Imposed, impact of bending neglected
- strain rate sensitivity — Same as for standard tensile tests
- Simplicity of assessment — Simple (friction & bending neglected)

Segmented expanding cone mandrel test (SCM)

The Segmented cone mandrel (SCM) test is used for defining the hoop direction material properties of nuclear fuel claddings. The loading of SCM is induced by expanding segments, which are placed inside a cladding tube as seen in Figure 7.

The following inputs are needed for the data analysis;

1. Load-displacement from the test: F vs u_z (see typical curve in Figure 8)
2. Ring sample geometry: height, wall thickness and inner diameter
3. Segment geometry : outer geometry and height
4. Cone geometry: angle (20° used in TASTE)
5. Friction coefficient between, cone/segment and segment/tube. The friction coefficient is the major unknown. For steels that are Teflon sprayed a typical value is 0.05. For steel-to-steel values of 0.15 to 0.2 care considered typical.



a) b)

Figure 7.The segmented cone mandrel test.

The stress-strain curves are computed directly from the load-displacement curve and the geometry of the ring sample and cone.

The axisymmetric analytical model gives an estimate on the stress-strain curve (σ_θ,$\varepsilon_{\phi\phi}$) by assuming purely plastic deformation and therefore no volume change. The known variables (see Figure 7a) are: the initial height (H_0^T) and thickness (t_0) of the cladding tube, the diameter ($2R_0^c$) and thickness (t_M) of the segments' lower part and the height of the segment (H^s), the angle of the cone (θ), the vertical displacement (u_z) and associated force (F_z) and the friction coefficient between the different friction surfaces (μ_1, μ_2, μ_3). The unkown parameters are: the contact pressure (p_1, p_2, p_3), the hoop stress (σ_θ), the height (H^T) and wall thickness (t) of the tube.

$$\left.\begin{aligned}
&\varepsilon_{\phi\phi} = \ln(1+\frac{u_z \tan(\theta/2)}{R_0^c + t_M}), \quad H^T = H_0^T(1+\frac{u_z \tan(\theta/2)}{R_0^c + t_M})^{\frac{-F}{F+G}}, t = t_0(1+\frac{u_z \tan(\theta/2)}{R_0^c + t_M})^{\frac{-G}{F+G}} \\
&p_1 = \frac{F_z}{A_c^{\Pr}(1+\mu_1/\tan(\theta/2))}, \\
&p_3 = \frac{F_z(1+\mu_2(\frac{1-\mu_1\tan(\theta/2)}{\tan(\theta/2)+1})}{A_M^{\Pr}(1+\mu_3\mu_2)}, \\
&p_2 = \frac{F_z}{A_T^L}[(\frac{1-\mu_1\tan(\theta/2)}{\tan(\theta/2)+1}) - \mu_3\frac{\left(1+\mu_2\frac{1-\mu_1\tan(\theta/2)}{\tan(\theta/2)+1}\right)}{1+\mu_1\mu_2}] \\
&where \quad A_c^{\Pr} = \pi[(H_0^s\tan(\theta/2)+R_0^c) - R_0^{c^2}], \quad A_M^{\Pr} = \pi[(H_0^s + R_0^c) - R_0^{c^2}] \\
&A_L^T = 2\pi H_0^T(R_0^c + t_M)\left(1+\frac{u_z\tan(\theta/2)}{R_0^c + t_M}\right)^{-\frac{F}{F+G}} \\
&\sigma_\theta = \frac{p_2(t_M + R_0^c)}{t}
\end{aligned}\right\}$$

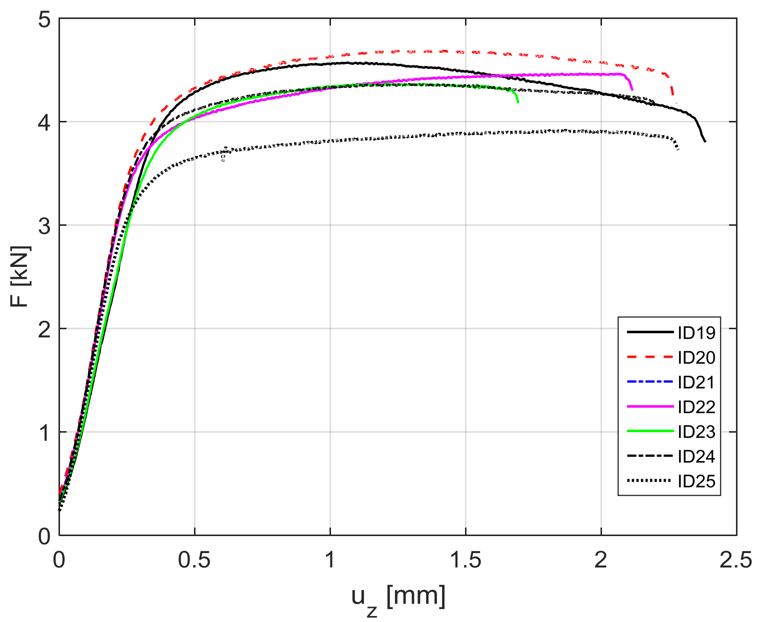


Figure 8. Recorded F versus u_z for room temperature tests of 15-15Ti.

The main disadvantage of the method is the large impact of friction on estimated yield and tensile strength.

The test features for this test type are estimated as:

• Material needed	20 specimen / 10 cm (5 mm rings)
• Test simplicity	Medium (segment placing tedious)
• Specimen preparation	Simple, tube ring
• Controlled load and displacement	Yes, both possible

- Hot-cell applicability — No (numerous small segment parts)
- Testing in corrosive loops — Unlikely
- Biaxiality, controlled or imposed — Some biaxiality from segments
- Strain rate sensitivity — Same as for standard tensile tests
- Simplicity of assessment — Medium/difficult (friction unknown)

Internal pressure test (IP)

In the classical internal pressure (IP) test for biaxial tensile and creep testing the stress state is imposed by internal pressure. In this test set-up, without added tensile loads, the axial–hoop stress ratio is constant factor of 2, i.e. axial stress is ½ the hoop stress. In the enhanced version of the test it is possible to control the ratio of hoop and tension stresses by adding an axial load for the tubular test specimen either in push or pull direction.

The elastic hoop stress caused by the internal pressure is;

$$\sigma_{\mathrm{el\ hoop}} = \frac{\mathrm{p}}{\mathrm{y}^2 - 1} \cdot (1 + (\frac{\mathrm{D_o}}{2}/\mathrm{r})^2)$$

where p is internal pressure, D_o is the outer diameter of the tubular specimen, r is the radius (from the middle point to the point of interest) and y = outer diameter D_o divided by the inner diameter of the tubular specimen.

The elastic axial stress caused by the internal pressure and an imposed axial load can be calculated as;

$$\sigma_{\mathrm{el\ axial}} = \frac{\mathrm{p}}{\mathrm{y}^2 - 1} + \frac{\mathrm{F_a}}{\mathrm{A}}$$

where F_a is axial force and A is the cross-sectional area of the tubular specimen.

The elastic radial stress can be calculated:

$$\sigma_{el\ rad} = \left(\frac{P}{y^2 - 1}\right) \cdot (1 - (\frac{D_o}{2}/r)^2)$$

A number of correlation equations [6] is proposed for transforming tensile strength and yield stress properties to burst pressure P_{max} such as:

A) The ASME correlation;

$$P_{max} = R_m \frac{k-1}{0.6k+0.4}$$

B) The Max Share stress correlation;

$$P_{max} = 2R_m \frac{k-1}{k+1}$$

where k is the ratio between outer and inner radius (R_o/R_i), for the TASTE cladding dimensions k=3.275/2.825=1.16 is giving P_{max} estimates of $0.145 \cdot R_m$ and $0.148 \cdot R_m$ respectively.

C) The Fletcher correlation, also given in given [6], is dependent on the flow stress $\sigma_{flow}=(R_m+R_{p02})/2$ and the uniform strain ε_u.

$$P_{max} = \frac{2\sigma_{flow}}{D_i(1-\frac{\varepsilon_u}{2})}$$

It is to be noted that the biaxial stress state in an internal pressure tests is suppressing the yielding and the yielding is expected to occur at approximately 1.12 times the uniaxial yield stress, depending on the ratio inner diameter over wall thickness (D_i/t), i.e. the ratio of hoop stress to von Mises stress.

In TASTE the internal pressure tests were creep tests at constant internal pressure (IPC). The internal pressure tests for tensile properties are though interesting for fuel pin mock-up testing.

The main shortcoming of the IP tests are the "large" amount of material needed for the tests. Furthermore, the IPC instrumentation for measuring the hoop and axial strains are located along the "gauge length" and hence the load control is a potential problem since material softening or cracking might lead to undesired fracture. For the IPB test the final fracture is the sought test result.

The test features for this test type are estimated as:

• Material needed	~2 specimens / 10 cm (50 mm tubes)
• Test simplicity	Medium (internal pressure)
• Specimen preparation	Difficult, leak tightness
• Controlled load and displacement	Yes, both possible
• Hot-cell applicability	Possible
• Testing in corrosive loops	Possible
• Biaxiality, controlled or imposed	biaxial in nature, control possible
• Strain rate sensitivity	Assumed same as for tensile tests
• Simplicity of assessment	Easy (correlation to R_m, R_{p02})

Small Punch test (SPT)

In a standard "tensile" SP tensile test, the hemispherical tip of a punch or a ball is pushed at a constant displacement rate (0.3 mm/min in TASTE) through the center of a (flat) disc shaped specimen. In the case of testing cladding tubes the specimen can be machined flat (miniature SP samples) or the tests are conducted on curved samples, i.e. partial sections of a tube as shown in Figure 9 (E-F). The imposed stress state in the specimen during the test is multiaxial in nature and the stress-strain evolution in the sample is complex. The stress-strain at the puncher contact point can be estimated by formulas derived from the Chakrabarty membrane stretch formulations [7].

The punching force in SP tensile testing is typically generated by a universal testing machine with specimen-specific holders (see Figure 9 A-D). The SP test set-up and testing procedure are currently being standardized by a workgroup of ECISS TC101.

Figure 9: SP Test set-up and specimen; A) Puncher, B) Puncher ball, C) Specimen, D) Clamping thread E) flat specimen (before and after test), F) curved tube specimen (before and after test).

A typical SP tensile force-deflection curve is plotted in Figure 10. The tests was in this case performed with a hemispherical punch with a diameter of 2 mm and a receiving hole diameter of 4 mm. For SP "tensile" testing the most common punch / ball diameters are 2.4 and 2.5 mm. Also smaller dimensions of the test set-up can be used such as for the TEM sized specimen that is only 3 mm in diameter and 0.25 mm thick and the receiving hole diameter is in the 1.75-2mm range. The puncher ball is then 1 mm in diameter.

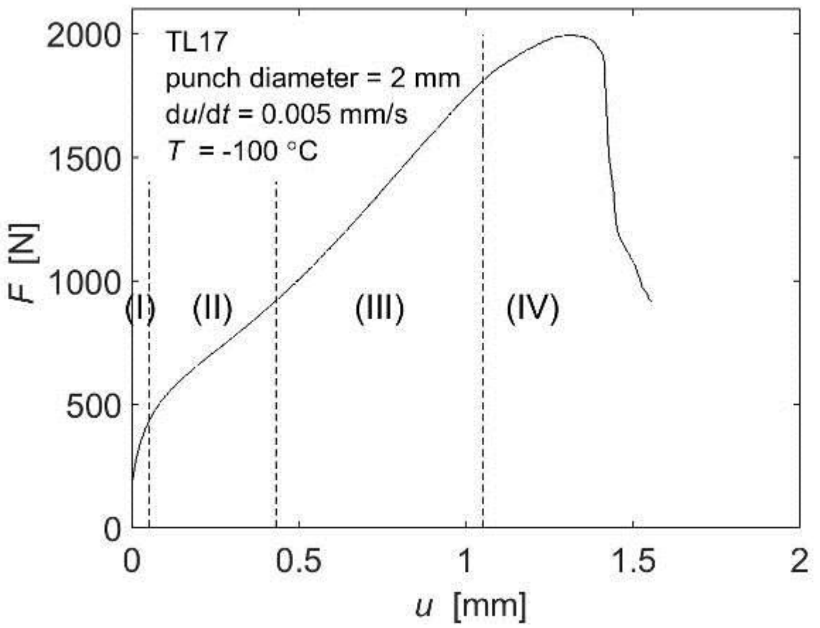


Figure 10. Force-deflection curve for a tensile SP test on Gr. 91 stainless steel at -100 ºC.

The estimation of the tensile material properties by SPT test is based on three characteristic values that can be derived from the force-deflection curve, i.e. the maximum force F_m, the deflection u_m at maximum force and the elastic-plastic transition force F_e. F_m is naturally the maximum force of the test. For the determination of F_e several approaches are currently discussed. In Figure 11 four different approaches are shown.

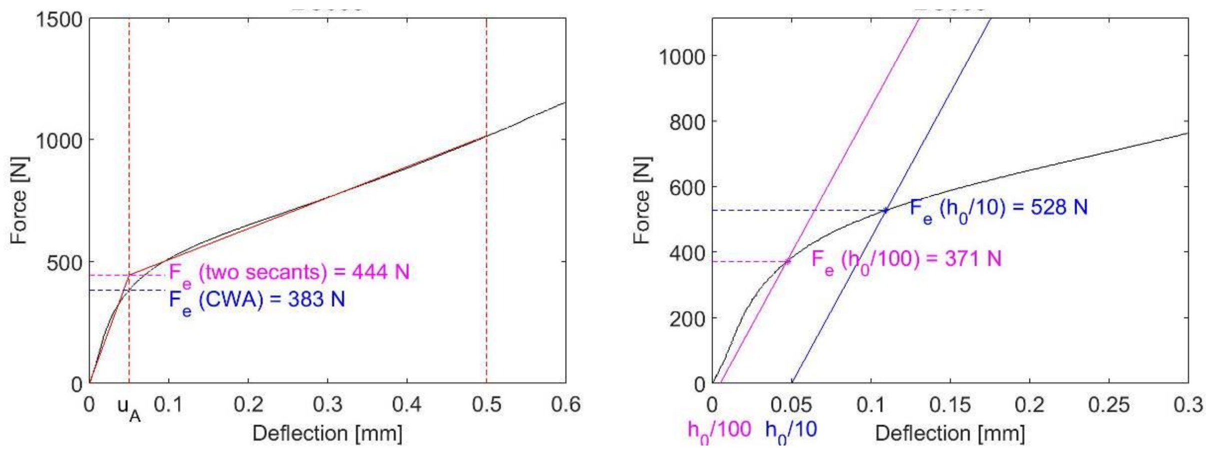


Figure 11 Extracting the F_e from the SP force-deflection curve by two-secants, the CWA and the offset method.

It is clear that correlating the yield stress to F_e will have different factors depending on which method is used.

The classical correlations for determining tensile strength and yield stress are:

$$R_{p02} = \alpha_1 \frac{F_e}{h_0^2} + \alpha_2$$

$$R_m = \beta_1 \frac{F_m}{h_0 u_m} + \beta_2$$

The α, and β parameter are correlation constants. Note that these constants are dependent on the test-setup, i.e. ball diameter, receiving hole diameter and clamping.

To compensate for differences in the test-setup dimensions and specimen thickness good estimates can be acquired by using the CWA formula intended for use in SP creep testing.

The ductility of the test material can be estimated by a SP fracture strain;

$$\varepsilon_f = \ln(\frac{h_0}{h_f})$$

Where h_0 is the initial specimen thickness and h_f the thickness adjacent to the area where failure occurred. The ε_f can also be estimated by the Chakrabarty formula for thinning in the ball-specimen contact boundary.

$$h^* = h_0 \left(\frac{cos\theta_0}{cos\theta}\right)^2$$

Where h* is the thickness at the contact boundary and the angles θ_0 and θ can be derived from the deflection. Note that these angles are dependent on the puncher and receiving hole diameters.

The main disadvantage of this tests is the multi-axial nature of the test and the limited inter-laboratory comparability induced by the different dimensions of puncher, receiving hole and clamping. This however will change when the methodology has been standardized.

Consensus on the best way to convert force to stress, including correlation constants has not yet been satisfactorily settled, but a promising engineering method will be applied for the 1515Ti tests results.

The test features for this test type are estimated as:

- Material needed — 30 specimen/10 cm (1/3 tube)
- Test simplicity — Easy /medium
- Specimen preparation — Medium (flat), simple tube sections

• Controlled load and displacement	Yes, both possible
• Hot-cell applicability	Possible
• Testing in corrosive loops	Possible
• Biaxiality, controlled or imposed	biaxial in nature, control possible
• Strain rate sensitivity	Assumed same as for tensile tests
• Simplicity of assessment	Easy (correlation to R_m, R_{p02})

Ring Compression test (RC)

In ring compression tests (RT) [8] the ring sample is compressed perpendicular to the tube axis under either displacement or load control. The main use of the ring-compression test has been as an effective screening test for ductility (aging, radiation hardening).

The tests can also be used for estimating tensile and creep properties. The main benefit of the test is the simplicity of the test specimen and test procedure. The main shortcoming of the method is that the deformation is highly non-homogenous with simultaneous tensile (outer surface, 3 and 9 o'clock) and compressive (inner surface, 3 and 9 o'clock) stresses. At 12 and 6 o'clock positions the situation is reversed.

A beneficial feature is also that the test method has no sensitivity to friction between the ring and the loading device.

The characteristic RC load-displacement curves are produced by applying a constant compressive displacement rate (for TASTE 0.2 mm/min). The maximum (equivalent) stresses are expected to be reached close to the inner surface at the 12 o’clock position as seen in Figure 12.

Due to the complex dynamic stress/strain evolution in the ring during the test the translation of the force-deflection curve into an equivalent stress-strain curve is not attempted in a simplified assessment. Instead a correlation between the descriptive "collapse" loads and the sought tensile properties are determined. For more advanced estimates Finite Element Analysis has to be used.

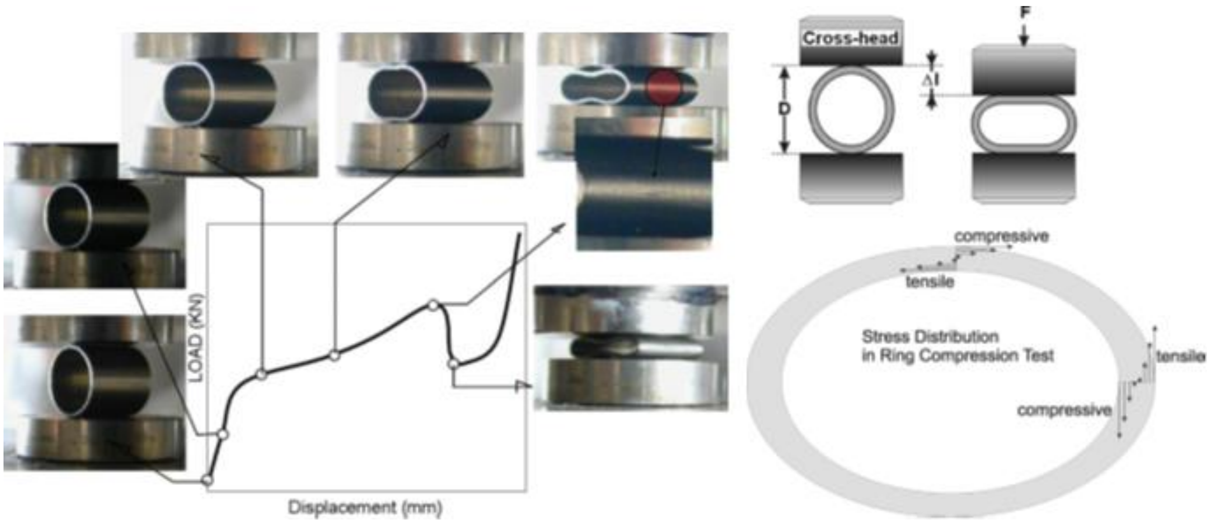


Figure 12. Stages of Ring Compression Test [1] and stress distributions in a RC test .

Estimates of the Yield Stress, Ultimate Tensile Strength and Strain to fracture can be acquired from theoretical models based on standard elastic theory and rigid linear strain-hardening.

The limit load P_0, (i.e. the load at which large plastic deformation is initiated) assuming elastic-perfectly plastic material properties can be defined as:

$$P_0 = \frac{4M_0}{R} = \frac{\sigma_0 t^2 \, l}{R}$$

where *R* is the initial radius of the ring, *l* the length of the ring and *t* the wall thickness.

The same relation can also be used with sufficient accuracy for strain hardening materials, i.e. the collapse stress can be obtained from the limit load P_0 as:

$$\sigma_0 = \frac{\alpha P_0 R}{t^2 l}$$

where α equals 1 if rings (length not greater than a few thicknesses) are tested and 0.866 if tubes (length not less than one diameter of the tube) are tested.

The calculated collapse stress can now be linearly correlated to the yield stress ($R_{p0,2}$) and ultimate tensile strength (R_m) through the following coefficients;

$$K_{Rp02} = \frac{\sigma_0}{R_{p02}}$$

$$K_{Rm} = \frac{\sigma_0}{R_m}$$

The collapse stress can be acquired from the experimental data by applying the two-tangents method as shown in Figure 13.

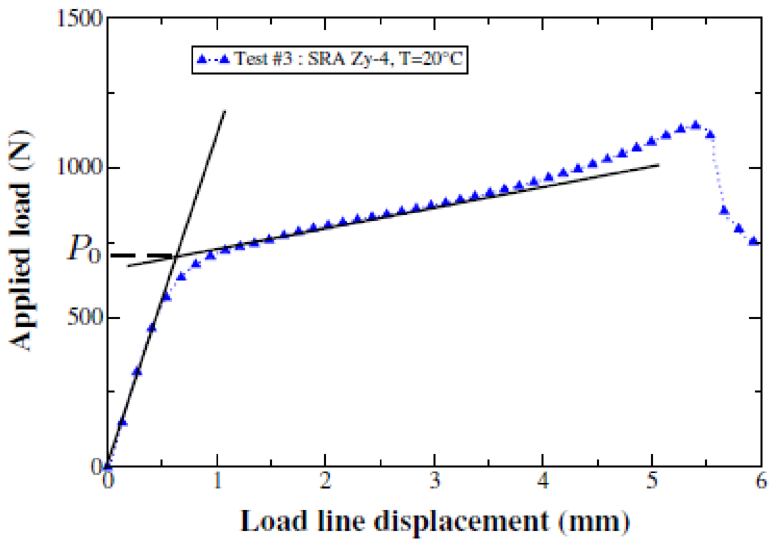


Figure 13. Extracting the collapse load P_0 from experimental data [8].

A clear draw-back of this procedure is that both yield stress and tensile strength are correlated against the same calculated collapse stress.

The test features for this test type are estimated as:

• Material needed	15 specimen/10 cm (ring)
• Test simplicity	Easy
• Specimen preparation	Easy
• Controlled load and displacement	Yes, both possible
• Hot-cell applicability	Possible
• Testing in corrosive loops	Possible
• Biaxiality, controlled or imposed	multiaxial in nature, imposed
• Strain rate sensitivity	Assumed same as for tensile tests
• Simplicity of assessment	Easy (correlation to R_m, R_{p02})

Creep Properties

The main sought creep properties are the strengths (to rupture $R_{u/T/t}$ or specified strain $R_{\varepsilon/T/t}$) as a function of temperature (T) and time (t), for instance the rupture strength at 600°C to give a life of 10 000h is $R_{u/600°C/10kh}$. To estimate rupture strength values only the time to rupture is needed for a test at specified temperature and stress. For a creep strain assessment also the time-strain evolution is needed for the specified stress and temperature.

Micro creep test (MCT)

The micro creep test is performed with specimen and equipment equivalent with the ones presented earlier for the micro tensile test. Creep tests differ only in the loading / stress state, i.e. creep tests are performed in constant load.

The strain-time creep curves at specified constant load can be used in the same manner as for standard creep test [9].

The test features for this test type are estimated as:

• Material needed	Minimal, large amount of specimen
• Test simplicity	Difficult (miniature specimen)
• Specimen preparation	Difficult (μEDM machining)
• Controlled load and displacement	YES, same as standard tensile
• Hot-cell applicability	Difficult
• Testing in corrosive loops	Difficult
• Biaxiality, controlled or imposed	Not applicable
• Strain rate sensitivity	Not applicable
• Simplicity of assessment	Simple

Internal Pressure creep testing (IPC)

Internal pressure testing of thin walled tubes can be performed with rather simple equipment when targeting only to record the rupture time at specified constant pressure. The IPC creep test requires that a constant pressure can be upheld during the testing, i.e. the volume change due to diametric changes have to be compensated for.

For acquiring creep strain information the test set-up has to be much more complex since the measurement of diametric change is during the test is challenging. The measurement can of course be performed by interrupted testing and measurement of the permanent diametric change. This approach is however time consuming and the interruptions can cause differences in the total rupture time by potentially introducing repeated primary creep response.

For the enhanced IPC test rigs it is also possible to change the biaxial stress state by applying additional axial load. This feature is needed if the anisotropic material properties are targeted. In the case of the purely internal pressure test the ratio of hoop to axial stress is a factor of 2.

For steady state creep stresses, the hoop stress for creep is:

$$\sigma_{Cr\ hoop} = P/(y^{2/\mathrm{n}} - 1) \cdot (1 + \left(\frac{(2-n)}{n}\right) \cdot (\frac{D_o}{2}/r)^{2/n}) \qquad (5)$$

Where n is the creep exponent for the power-law creep. The axial stress for creep is:

$$\sigma_{\mathrm{Cr\ axial}} = \mathrm{P}/(\mathrm{y}^{2/\mathrm{n}} - 1) \cdot (1 + \left(\frac{(1-\mathrm{n})}{n}\right) \cdot (\frac{\mathrm{D_o}}{2}/\mathrm{r})^{2/\mathrm{n}}) + {}^{\mathrm{F_a}}/_{\mathrm{A}} \quad (6)$$

The radial stress for creep can be calculated:

$$\sigma_{Cr\ rad} = P/(y^{2/\mathrm{n}} - 1) \cdot (1 - (\frac{D_o}{2}/r)^{2/n}) \quad (7)$$

The Von Mises stress for creep can be calculated as follows:

$$\sigma_{Cr\ VM} = \frac{1}{\sqrt{2}} \cdot \sqrt{((\sigma_{Cr\ hoop} - \sigma_{Cr\ axial})^2 + (\sigma_{Cr\ axial} - \sigma_{Cr\ rad})^2 + (\sigma_{Cr\ rad} - \sigma_{Cr\ hoop})^2} \quad (8)$$

The skeletal stress can be calculated as:

$$\sigma_{\mathrm{skeletal}} = \mathrm{P} \cdot \frac{\sqrt{3}}{\mathrm{y}^2 - 1} \cdot (\frac{(\mathrm{y}^2 - 1)}{\mathrm{n}}/(\mathrm{y}^{2/\mathrm{n}} - 1))^{\mathrm{n}/(\mathrm{n}-1)} \quad (9)$$

The main drawback of this test is the complex measurement set-up needed for measuring diametric (hoop) strains since the location where the main deformation occurs is not necessarily mid tube. Also for the creep life assessment the choice of reference stress is not always clear. The potential candidates for stress-rupture can be hoop stress, the von-Mises stress or the skeletal stress.

The test features for this test type are;

• Material needed	2-3 specimens / 10 cm (30 mm tubes)
• Test simplicity	Medium/difficult (diametric strain)
• Specimen preparation	Difficult, leak tightness
• Controlled load and displacement	Yes, both possible
• Hot-cell applicability	Possible
• Testing in corrosive loops	Possible
• Biaxiality, controlled or imposed	biaxial in nature, control possible
• Strain rate sensitivity	Not applicable
• Simplicity of assessment	Medium (use hoop, VM or skeletal?)

Small-Punch – Creep test (SPC)

For SPC testing there are several different test machine designs. The most common being the top loaded dead weight machine. The SPC test is conducted with the same test-setup and samples as for the SPT test except the loading mode is constant load. A SPC time-deflection curve is given in Figure 14 to be compared with a uniaxial creep

curve in Figure 15. In Figure 16 some P91 SPC creep rupture results plotted showing (expected) scatter between different types of testing machines.

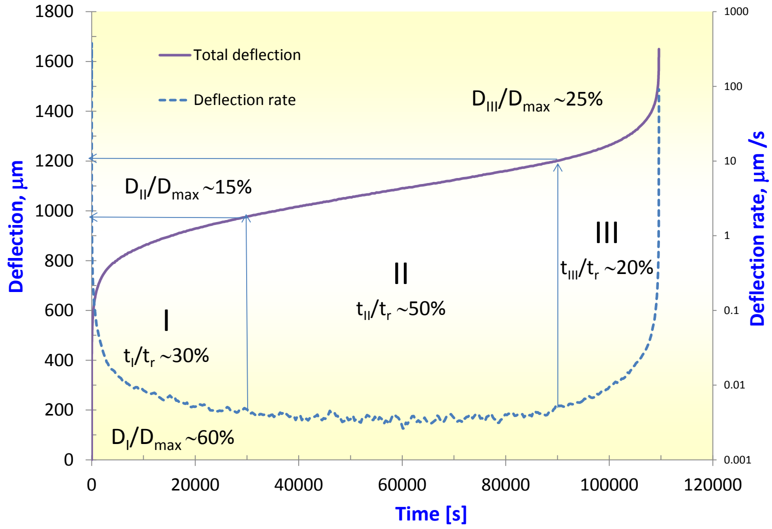


Figure 14. . SP creep deflection and deflection rate as a function of time for a 600 °C / 364 N test.

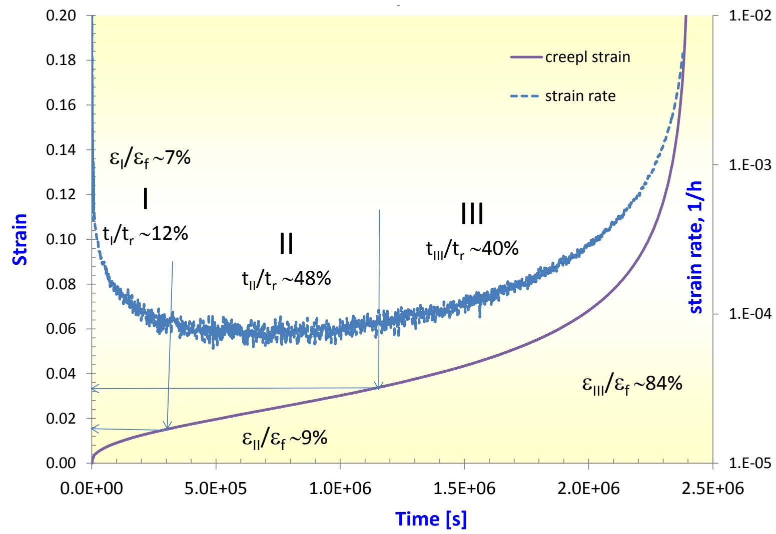


Figure 15. Uniaxial creep strain and strain rate as a function of time for a 600 °C / 155 MPa test.

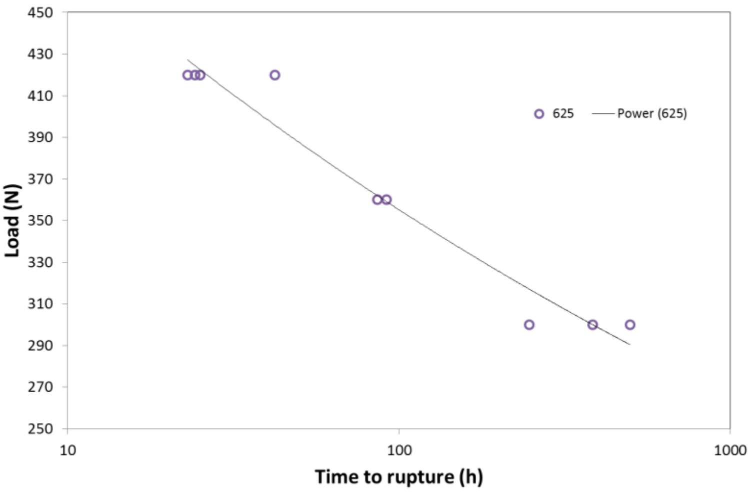


Figure 16. SPC creep rupture test results at 625°C for P91 steel. The data is from 3 different testing machines.

SPT creep tests have been successfully used for assessing a range of ductile materials (mainly F/M steels used in conventional power plants). The tests have also been used for ranking semi-brittle to brittle super alloys at high temperatures.

The main challenge of SPC as a testing technique to estimate the uniaxial creep properties is the conversion ratio of the load in a SPC test (F) into the corresponding stress (σ) in a uniaxial creep test. In the current CoP [10] the following relationship is given for the load over stress ratio F/σ;

$$F_{SP} / \sigma = 3.33 \cdot k_{SP} \cdot R^{-0.2} \cdot r^{1.2} \cdot h \quad (10)$$

where *R* is the radius of the receiving hole, *r* the radius of the puncher or ceramic ball, *h* the specimen thickness and k_{SP} is the non-dimensional SP ductility parameter. The default value of $k_{SP}=1$. However, it has been shown that the k_{SP} parameter deviates from unity for a number of materials and especially for longer test durations.

It was found that the creep tests performed with the target TASTE material 1515 Ti behaved in a creep-brittle fashion. Early cracking of the material in the initial phase of loading or creep before reaching "steady state" creep straining makes assessment of both rupture and creep deflection rate impossible. The few tests performed with a smaller puncher ball (∅2 mm instead of the ∅2.5 mm) had seemingly less cracking issues and could potentially indicate that testing with the TEM disk size specimen and the ∅1 mm ball could be successful.

The main draw-back of this test is the complex multi-axial stress state and the unclear Force to stress conversion factor.

The test features for this test type are;

- Material needed — 30 specimen/10 cm (1/3 tube)
- Test simplicity — Easy /medium
- Specimen preparation — Medium (flat), Simple tube sections
- Controlled load and displacement — Not applicable
- Hot-cell applicability — Possible
- Testing in corrosive loops — Possible
- Biaxiality, controlled or imposed — multi-axial in nature
- Strain rate sensitivity — Not applicable
- Simplicity of assessment — Medium (correlation to R_m, R_{p02})

Discussion

The TASTE test programme has made it possible to compare a number of test techniques requiring different amount of material. The large amount of data acquired on the different test types for 1515Ti steel will give an improved insight in the usability, simplicity and robustness of estimates of each technique.

It is suggested that the testing of fuel cladding materials and sub-sized specimen techniques are continued within the EEAR JPNM for further insight in this important topic.

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