Application of the Omega Method (API 579-1/ASME FFS-1) to the life assessment of a service exposed component and possible, further investigations on welded joints creep behaviour

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Keywords

MPC Omega Method, creep behaviour, remaining life, creep range, creep tests, service conditions, petroleum refinery, fired heaters, welded joints, pressure equipments

Introduction

The present paper deals with an example of application of the Omega Method procedure to the remaining life assessment of a radiant coil of a hydrocarbon fired heater. The procedure, elaborated by the American Petroleum institute (API) and by the "Material Properties Council", has been included in the latest edition of API 579-1 / ASME FFS-1 (2007). An advantage of the procedure is the capability to evaluate the remaining life of a component through the execution of accelerated creep tests on service exposed materials, even in absence of information on past service history.

While traditional methods based on stress rupture tests (like isostress testing) require long range extrapolation of short term stress-rupture test results, the Omega Method allows for a significant reduction of test duration without affecting, in the mean time, extrapolation reliability.

Despite this procedure has been elaborated and extensively tested for base materials (a large set of data is available in API 579-1 Appendix F for the most common materials used in petrochemical and power generation plants), the methodology criteria may be successfully applied for an effective and functional conformity evaluation of weld metals addressed for high temperature application.

Description of the Omega Method

The Omega Method is based on assumptions partly conflicting with the classic formulation of the creep damage mechanism. The classic theory considers 3 stages in the evolution of creep strain vs. time (Figure 1):

- Primary creep, in which creep strain rate decreases with time;
- Secondary creep, in which creep strain rate is constant in time (whose duration is usually dominant in component life);
- Tertiary creep, in which creep strain increases with time until rupture occurs.

The Omega Method is based on the assumption that, after the "primary creep" stage (often characterized by negligible strain and short duration), a continuous increase in strain rate occurs, according to the equation:

$$\frac{\dot{\varepsilon}(t)}{\dot{\varepsilon}_0} = \frac{1}{1\text{-}\Omega\dot{\varepsilon}_0 t} = e^{\Omega\varepsilon_c} \quad (1)$$

in which:

- "$\dot{\varepsilon}_c$" is the strain rate at the end of primary creep stage; it depends on stress, temperature and material;
- "Ω" is a dimensionless parameter which describes the evolution of creep strain with time; it depends on stress, temperature and material;
- "t" is the time from the end of primary creep stage to the considered instant;
- "ε_c" is the accumulated creep strain at time "t" (the creep strain produced during the "primary creep" stage is neglected).

The Omega Method, therefore, suggests a new model for the description of creep strain evolution with time: starting from the observation that, at design stresses, primary creep is usually small and of short duration and the secondary creep is nearly non-existent, the model considers that all the life of the components operating in the creep range is spent in the tertiary phase (Figure 2).

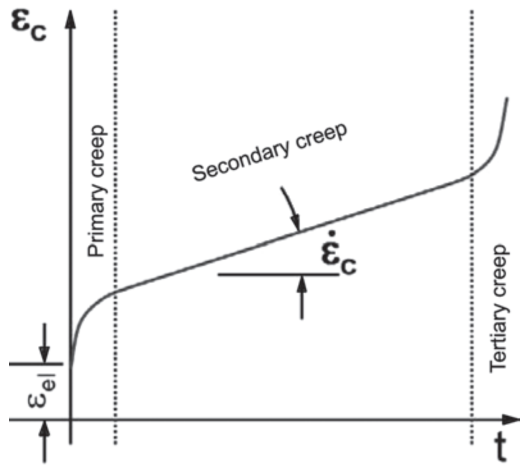

Figure 1. Creep strain curve (traditional approach)

On the basis of the proposed model, creep rupture occurs when strain rate becomes infinite; as a consequence, time to rupture t_R (from the end of primary stage) is given by the following relationship:

$$t_R = \frac{1}{\Omega\dot{\varepsilon}_0} \quad (2)$$

If the component has been operated for a service period "t", the remaining life "t_R - t" is defined by the equation:

$$t_R - t = \frac{1}{\Omega \dot{\varepsilon}(t)} \quad (3)$$

where "$\dot{\varepsilon}(t)$" represents the value of strain rate after the service time "t".

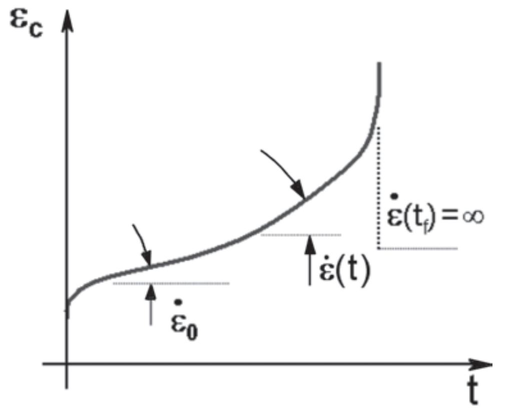

Figure 2. Creep strain curve (Omega Method approach)

For both "Ω" parameter and "$\dot{\varepsilon}(t)$" a polynomial parametric relationship can be adopted, which is similar to the traditional Larson Miller approach:

$$PLM_{SR} = [log\dot{\varepsilon}(t) + A_0(t)]T = -\sum_{K=1}^{n} A_k (log\sigma)^{k-1} \quad (4)$$

$$PLM_{\Omega} = [log\Omega - B_0]T = \sum_{K=1}^{n} B_k (log\sigma)^{k-1} \quad (5)$$

where "σ" represents the applied stress and "T" the absolute temperature. All coefficients A_k and B_k are dependent on the considered material; $A_0(t)$ is also dependent on the considered instant "t". Values obtained by MPC Omega Project are given in API 579-1 Appendix F for a large set of materials commonly used in petrochemical and power generation plants; A_0 is given for non-exposed materials ($t = 0$).

Ω can also be obtained by accelerated creep tests in which strain is recorded, interpolating the data (ln, ε_c), according to the following relationship:

$$ln\dot{\varepsilon} = \Omega\varepsilon_c + ln\dot{\varepsilon}_0 \quad (6)$$

When the Omega Method is adopted for a remaining life assessment it is sufficient to estimate creep strain rate at service stress and temperature through creep tests carried out on the service exposed material. Deducing Omega by literature data it is then immediate to evaluate the remaining life through equation (3).

When a service-exposed material sample is available for tests, it may be opportune to run a mixed test program in which some tests are brought to rupture (with duration of about 1000-2000 hours) in order to allow the evaluation of Omega and therefore the comparison with literature data. In this set of creep tests temperature may be increased up to 60-80°C more than the service temperature, while test stresses are of the same level of service stresses. From the results of this first set of tests it is possible to evaluate Omega values for different stresses and temperatures for the material under consideration and compare them with the mean values given by API 579-1. In such a way the Omega values given by API 579-1 may be adopted with a good reliability in the remaining life assessment, for different levels of stress/temperature.

The second set of creep tests includes "interrupted" tests, with duration ranging from 100 hours to 300 hours, carried out at conditions of stress/temperature very close to the service ones, with the aim of determining the current strain rate. They can be interrupted as soon as the current strain rate has been measured.

It is opportune to carry out the tests on samples taken from the zones exposed to higher temperatures, (e.g. the flame side of heater tubes). From the experiments executed by Prager, test results are fairly independent from the drawing direction of the specimen; when sample geometry makes onerous the machining of transversal (circumferential) specimens, it is then possible to adopt longitudinal specimens. Within the activities described in this report, however, some tests have also been executed on transversal specimens, as described in detail in the following paragraphs, in order to investigate creep behaviour in both directions.

It may be underlined that the integral adoption of API 579-1 procedure also includes some corrective parameters in order to take into account some factors (e.g. triaxiality of the stress state and material ductility) that may affect the remaining life assessment.

Example of application of "Omega Method" to a fired heater radiant coil

Within a Maintenance Turn-Around scheduled for the life assessment of a refinery heater according to Italian regulations and standards (Circolare ISPESL N° 48/2003) some of radiant coil tubes had to be replaced because of the presence of significant thinning phenomena.

Besides the traditional remaining life assessment according to Circolare ISPESL N° 48/2003 prescriptions (which is basically based on the Larson Miller approach) a further evaluation has been performed adopting the "Omega Method" procedure proposed in API 579-1, on the basis of creep tests carried out on service-exposed material. The specimens drawn for creep tests have been conservatively taken from sample flame side, which is commonly exposed to higher temperatures and where the creep damage is presumably higher.

The equipment under consideration has been operated for about 200000 h. Design conditions are indicated hereafter:

- design pressure: 1.79 MPa;
- design temperature: 621°C.

Pressure and temperature recordings were unfortunately available only for the latest service period; in the traditional remaining life assessment according to Larson Miller approach, therefore, the assumption of conservative hypotheses was necessary to undertake the assessment.

The radiant coil is manufactured in ASTM A335 P5. The pipes are 6" nominal diameter, 7.11 mm thick (minimum measured thickness 6.0 mm).

Creep test program

Taking into account the indications given in technical literature and API 579-1 for the adoption of "Omega Method" and considering operating conditions foreseen by the user for further service, the test program has been defined according to the following criteria:

- five tests have been carried out on longitudinal specimens in order to determine the current strain rate, at two different

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temperature values (600°C and 625°C) and stress values as close as possible to those acting in service. The choice of test conditions has been obviously constrained by strain-gage capability to appreciate small strain rate values (approximately between 3×10^{-6} h^{-1} and 5×10^{-5} h^{-1}). Test conditions and obtained results are summarized in Table 1;

Table 1. Test conditions and obtained current strain rate values ("SR") in longitudinal test

Test ID	$T(^0C)$	T(K)	σ(MPa)	$SR(h^{-1})$
S1	600	873.15	50.7	5.75E-05
S2	600	873.15	40.3	6.11E-06
S3	625	898.15	29.9	5.09E-06
S4	625	898.15	35.3	1.26E-05
S5	600	873.15	44.9	1.78E-05

- further two tests have been carried out on transversal (circumferential) specimens, in order to compare material behaviour in both directions. Because of sample geometry, the specimens have been manufactured by welding threaded ends to a central section machined in circumferential direction. In order to minimize the influence of welds on specimen behaviour, the LASER equipment of IIS Laboratory has been used. Additional longitudinal specimens with a "reduced" gage length (equal to the transversal specimen) have been tested in order to investigate the influence of geometry on test results (Figure 3).

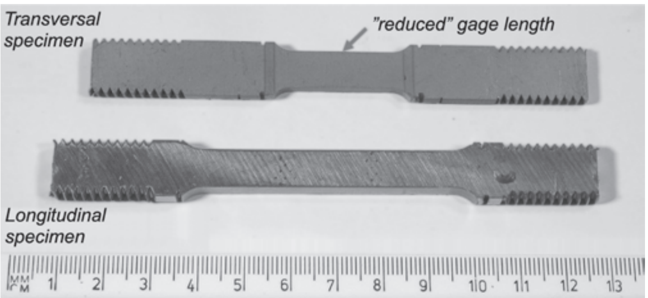

Figure 3. Geometry of longitudinal and transversal specimens

Transversal specimens (and additional longitudinal specimens with reduced gage length) have been subjected, for comparison, to two test conditions adopted for longitudinal specimens S2 and S4 (see table 1).

All specimens have been machined according to EN 10291 prescriptions ("Metallic materials - Uniaxial creep testing in tension - Method of test"). All tests have been carried out under constant load, with continuous monitoring of creep strains.

It has not been considered necessary to include in the program the execution of creep tests for the definition of "Ω" parameter. As the material under examination is rather common in petrochemical applications, in fact, it has been assumed that the data given for 5Cr-0.5Mo steels can be reliably adopted for the assessment. Such hypothesis, moreover, had been checked in the past through creep tests brought to rupture within experimental programs carried out on service exposed material samples in ASTM A335 Gr. P5.

As shown in Figure 4, tests carried out in circumferential direction seemed to show lower strain rates than those recorded in longitudinal direction under the same conditions. However the further additional tests on longitudinal specimens with reduced gage length (having the same geometry of transversal ones) showed that there is not substantial difference in testing results related to drawing direction of specimen. The different trend initially observed was only due to specimen geometry.

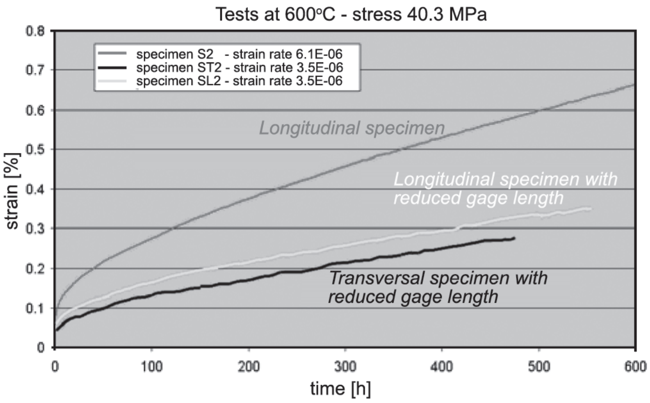

Figure 4. Comparison of test results on longitudinal and transversal specimens (for test condition S2)

All tests have shown a satisfactory agreement with the model proposed by the Omega approach, as shown in Figure 5, in which the experimental results for longitudinal specimens are plotted. The diagram correlates applied stress and "strain rate parameter" "PLM_{SR}" (Eq. (4)). The red curve represents the average behaviour of non-exposed material according to API 579-1 data; open symbols indicate creep test results if the coefficient $A_0(t = 0)$ is used (which is representative of non-exposed material). As it can be noticed, they fall well above the curve, as experimental strain rates are considerably higher than those expected for non-exposed material according to API 579-1 data. It is however immediate to find a proper $A_0(t)$ value (full symbols) so that all tests results, with very good approximation, fall onto the curve. This result, therefore, seems to confirm the reliability of the model proposed by the "Omega Method".

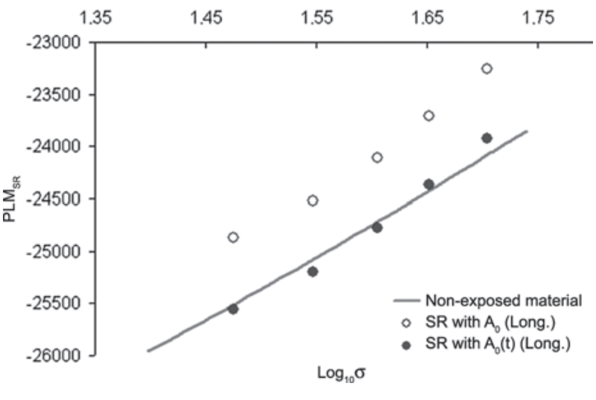

Figure 5. Representation of test results: comparison with average non-exposed material (red curve)

The values of $A_0(t)$ which correspond to the best fit of experimental data through the API 579-1 curve is: -23.16.

On the basis of the above indicated equations describing the Omega approach, it is also possible to calculate the consumed life fraction "f", according to the following relationship:

$$f = 1 - \frac{\dot{\varepsilon}_0}{\dot{\varepsilon}(t)} = 1 - 10^{[A_0(t) - A_0(t=0)]} \quad (7)$$

If the average behaviour indicated by API 579-1 for non-exposed material is considered (which means to assume $A_0(t = 0) = -22.4$), Equation 7 leads to "*f*" value of about 83%.

Remaining life assessment on the basis of creep test results

The "Omega Method" procedure (described in detail in API 579-1, Sec. 10 and Annex F) has been adopted to evaluate the remaining life of radiant coil components, on the basis of strain rate data obtained from creep tests. The assessment has been performed for several temperature values, ranging from 570°C to 621°C (design temperature), under the hypotheses summarized in Table 2.

Table 2. Hypotheses adopted for the assessment

Maximum operating pressure	p_e=	1.275 MPa
Component thickness (minimum measured value)	t=	6.0 mm
Von Mises stress	σ_{eq}=	18.9 MPa
Safety factor (indicated in Italian standard Circolare ISPESL N°48/2003)	C_S=	0.8
Assessment stress (σ_{eq}/C_S)	σ_c=	23.6 MPa
"Parger Factor" (API 579-1 Annex F)	β=	0.33
Coefficient δ_Ω (API 579-1 Annex F)	δ_Ω=	0.08
Coefficient α_Ω (API 579-1 Annex F)	α_Ω=	2.00

The current strain rate corresponding to stress and temperature values considered in the assessment has been extrapolated from experimental data. Remaining life values are summarized in Table 3.

Table 3. Remaining life assessment according to "Omega Method"

T(°C)	T(K)	$\Omega^{(1)}$	SR(h^{-1})$^{(2)}$	$n_{BN}^{(3)}$	$\Omega_m^{(4)}$	RL(h)$^{(5)}$
570	843.15	33.78	1.60E-08	6.65	48.34	>1000000
580	853.15	31.21	3.69 E-08	6.57	44.73	605238
590	863.15	28.89	8.35 E-08	6.49	41.49	288509
600	873.15	26.79	1.85 E-07	6.42	38.58	139800
610	883.15	24.89	4.04 E-07	6.34	35.95	68820
621	894.15	22.99	9.34 E-07	6.27	33.35	32121

Notes:
(1) Omega parameter simulated on the basis of API 579-1 data
(2) Extrapolated current strain rate
(3) Strain rate exponent (API 579-1, Annex F)
(4) Modified Omega parameter (takes into account stress three-axial effects, see API 579-1, Annex F)
(5) Remaining life

Application of Omega methodology to weld metal creep strength estimation

It is well known that creep damage in high temperature components is predominantly found in weldments: welded joints generally exhibit lower creep strength than the base metal. The decrease in creep strength of the welded joint is more pronounced at long rupture lives and/or higher temperatures.

The major cause of this life reduction is a mis-match in the creep properties, primarily the minimum creep rates of the weld, heat affected zone and parent metal. This mis-match causes constraints and stress concentrations which are enhanced by other factors like weld geometry and state of loading. Different failure modes (e.g. Schuller classification) may manifest depending if either a creep-soft or a creep-hard weldment occurs. In any case the higher the mis-matching, the more complex is the local stress state and consequently the lower the weld creep strength. The reduction in rupture life caused by the introduction of a weld depends on the magnitude of mismatch in the creep properties. For homogeneous welded joints a filler metal having a creep behaviour as much as possible similar to the parent metal can give improved creep performance of welded joint.

Attempts have been made to use the data from cross-weld creep tests to obtain life reduction factors. However the stress states in a weld and in a cross-weld specimens are generally significantly different and hence the direct application of cross-weld data for obtaining life reduction factors may lead to unreliable and sometimes non conservative results. On the other hand the "component tests" are not technically feasible and too costly.

While design lives for new plants are required to last up to 200000 hours and more, very few data on welded joint creep resistance are available, and usually the design codes require, in absence of information, a reduction factor which can range, depending on the code, from 0.5 (e.g. ASME B31.3, ASME III) to 0.8 (EN 13445, EN13480). In particular, EN 13445, Part 2 includes in Annex C an experimental creep test program in order to evaluate weld creep reduction factor, but stress-rupture tests up to 30000 hours are required for a reliable estimation, not compatible with industrial times and costs.

One of the PED requirements is the evaluation of weld metal creep strength. Also the present draft of EN 14532 Part 2 asks for creep stress rupture tests on all-weld metal specimens; acceptability criteria are based on creep properties of base materials of corresponding chemical analysis.

What seems to be needed is a simple, universal, reliable and reasonably cheap check test capable to show that one filler metal is suitable for high temperature application. This can be represented by the application of Omega methodology to longitudinal all weld metal specimens. The Omega procedure can determine, by the execution of a few short-duration tests, the creep strain rate of weld metal SRWM at service conditions and compare it to the creep strain rate of base metal SRBM (which is available for a large set of materials in appendix F of API 579-1). Acceptability criteria based on SRWM/SRBM ratios may be proposed.

An experimental research project, including Omega tests on both weld metal and base metal specimens and traditional cross-weld results for validation purposes is starting up among industrial and research partners in Italy.

Conclusions

In this paper an application example of the assessment procedure known as "Omega Method" has been described. This approach, which can be adopted to evaluate the remaining life of components operated at high temperatures within the creep regime, is proposed by the latest edition of API 579-1/ASME FFS-1.

When joined to a proper creep test program on post-exposed material samples, the procedure seems to offer a reliable and functional tool for the assessment of components whose service history is partly or completely unknown. If compared to traditional testing approaches, the adoption of "interrupted" tests aimed to the definition of the current strain rate allows reducing test duration without affecting assessment reliability, as test parameters significantly closer to actual operating conditions can be adopted.

Among pressure equipments in petrochemical plants, the method seems to be particularly suitable to the assessment of fired heaters, where material samples can be easily obtained without the need for expensive and/or critical repairs and service conditions (in terms of temperature and stress distributions) are reasonably uniform. In this field, therefore, the described approach can opportunely support the User when decisions are needed about maintenance strategies and/or enquiries of Regulatory Bodies about safety and reliability of components have to be examined.

Another interesting application of the methodology is addressed to weld metal creep strength assessment, in particular for the conformity evaluation of filler metals for high temperature applications according to PED requirements.

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