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Macroscopic results of long-term creep on a modified 9Cr–1Mo steel (T91)

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ABSTRACT

Modified 9Cr–1Mo steel specimens were subjected to creep tests at temperatures ranging from 500 to 600 °C. One test at 500 °C ruptured after approximately 160,000 h and another at 600 °C ruptured after approximately 94,000 h. Two tests at 500 and 600 °C are still under creep having not ruptured after more than 170,000 h. These tests show that the Monkman–Grant relationship between minimum creep rates and time to fracture holds for a wide range of temperatures and applied stresses. It is also observed that there is a clear change in creep mechanism from power-law creep to viscous creep as well as a transition from significant reduction of area to virtually no reduction of area during creep at 500, 600 and 625 °C as it is mentioned in the literature for the higher temperatures.

High chromium ferritic-martensitic steels have been widely used as fossil energy plant materials [1,2]. Martensitic steels, when compared with austenitic steels, have lower irradiation-induced swelling, lower thermal stress, lower induced activation, lower thermal expansion, higher thermal conductivity and higher fatigue strength at high temperatures [2,3]. These steels are currently being investigated as candidates for structural applications in fusion reactors [1–6] as well as structural applications for long-term, high-temperature use in the next generation of fission power plants [7,8]. Currently, long-term creep strength properties are extrapolated from short-term data based on simple parametric methods [8,9]. However, for component lifetimes beyond 100,000 h, the prediction is still difficult and requires the knowledge and assessment of microstructural changes that are likely to occur during service [8].

To study the ferritic-martensitic steels for long lifetime service, creep tests were carried out using a modified 9Cr–1Mo steel, namely T91. Creep tests were conducted at several temperatures with a range of applied stresses. Since high-temperature creep strength is one of the main factors in material life expectancy, knowledge of the long-term behavior of materials is necessary for effective and reliable design. This paper will present data for creep specimens that fracture after more than 90,000 h as well as data for tests still running with over 170,000 h of creep time.

1. Experimental procedure

The modified 9Cr–1Mo steel used in the present study was taken from a 300 mm plate produced by Creusot-Marrel from a forged 45 ton ingot with yield strengths (0.2%) of 363 MPa at 500 °C and 276 MPa at 600 °C. The chemical composition and thermal treatments are given in Tables 1 and 2.

The creep program is described in Table 3. The creep tests were carried out at constant load using samples of 85 mm length, a gauge length of 40 and a diameter of 5 mm. They were taken in a distance of one-fourth and three-fourth of the plate width.

2. Monkman–Grant relationship

Various methods have been used to predict the long-term behavior of materials at high temperature under stress. One theory, proposed by Monkman and Grant, suggests that there is a linear relationship between the logarithm of the time to rupture and the logarithm of the minimum creep rate. If this relationship exists, then the Monkman–Grant (MG) curve provides a very simple and powerful means of extrapolating long-term materials behavior from short-term test data [10], at least if the minimum creep rate can be evaluated.

Fig. 1 shows the minimum creep rate versus the time to fracture for our data and the data mentioned in the literature [8,11,17]. A Monkman–Grant relationship permits indeed a reasonable modeling of the data using Eq. (1) where t_r is the time to rupture of the creep specimen in hours, $\dot{\varepsilon}_{\min}$ is the minimum creep rate in s^{-1} and

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Table 1
Chemical composition of Creusot-Marrel modified 9Cr–1Mo material.

Element	Wt.%
C	0.106
S	0.003
P	0.009
Si	0.47
Mn	0.38
Ni	0.12
Cr	9.00
Mo	1.01
V	0.21
Nb	0.07
N	0.053

Table 2
Thermal treatments for Creusot-Marrel modified 9Cr–1Mo material.

Material	Transformations	Thermal treatments		
		Heat treatment	Quenching	Tempering
Creusot-Marrel	Forged and rolled	1070 °C/7 h	Water quench	760 °C/8 h

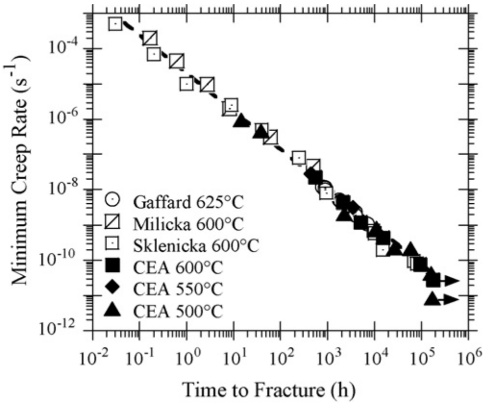

Fig. 1. Monkman–Grant curve with minimum creep rate versus time to fracture for T91 at temperatures ranging from 500 to 625 °C.

B and *n* are constants.

$$t_r = \frac{B}{\dot{\varepsilon}^n_{\min}} \tag{1}$$

In this case, *B* is equal to 3.9×10^{-5} and *n* is equal to 0.93.

Our data include four creep tests that are near or above 100,000 h for the time to fracture. Two of these tests have lead to failure and two tests are still running. The two tests which are still running have accumulated more than 170,000 h each and are indicated by the arrows pointing to the right in Fig. 1.

As a means of loosely predicting the fracture time of our specimen that is still running at 600 °C, we employed the ratio of the time to reach the beginning of the tertiary stage to the time to fracture for our test at the same temperature which lead to rupture after 94,000 h. Comparing the two samples in this manner gives an estimated fracture time of around 230,000 h for the sample still running at 600 °C. Using this fracture time of about 26 years, the Monkman–Grant curve will still permit an adequate prediction.

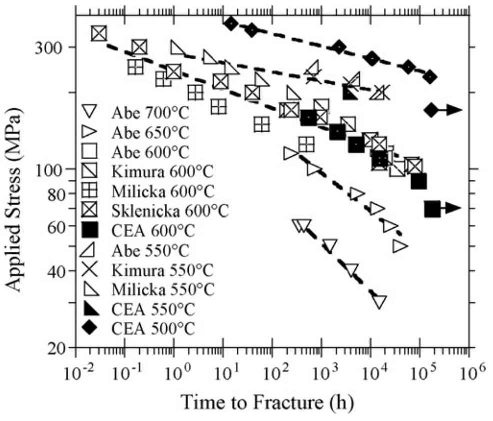

Fig. 2. Applied stress versus time to fracture for T91 for temperatures ranging from 500 to 700 °C.

In terms of predicting long-term behavior from short-term tests, the Monkman–Grant relationship is a very promising and potentially very powerful method. As our tests illustrate, certainly at times up to 160,000 h and potentially for even longer times, the MG relationship holds. We have found that this relationship and the aforementioned parameters allow for an accurate description of T91 creep lifetime for a whole range of temperatures and applied stresses until lifetimes of about 200,000 h. Moreover, some literature studies show that physical models based on the constrained creep cavities growth lead to the simple MG relationship when applied at low stresses [18,19]. It is nevertheless questionable to predict lifetime using this model for specimens with a high percentage of reduction of area.

3. Stress versus time to fracture

It has been suggested that although short-term tests indicate a linear relationship between the logarithms of the applied stress and the time to rupture, there is, in fact, a sigmoidal inflection at long lifetimes [9]. Kimura et al. [9] and Abe et al. [14] discuss an increase in the slope of the stress versus time to fracture with decreasing stress due to a loss of creep strength.

Plotting our data plus data from the literature [8,11,14,15] in the same fashion (Fig. 2), it is observed that no true conclusive inflection is seen at all temperatures. Although Abe et al. [14] and Kimura et al. [9] mention a dramatic increase in the slope above 10,000 h at many temperatures, we can only definitively see this inflection for the current data at 650 °C.

However, if we consider the estimated time to fracture defined in Section 3 (230,000 h) for our test still running at 600 °C, there would be an inflection point above 100,000 h at this temperature. If the test at 600 °C indicates a change in slope above 10^5 h, then

Table 3
Creep program on Creusot-Marrel modified 9Cr–1Mo material (ruptured and in progress tests).

Temperature (°C)	Stress (MPa)	Rupture time (h)	Temperature (°C)	Stress (MPa)	Rupture time (h)
500	370	14.8	550	200	34,63
500	350	39	600	160	543
500	300	22,95	600	140	21,03
500	270	10,396	600	125	50,22
500	250	59,347	600	110	14,946
500	230	162,900	600	90	93,749
500	170	178,030 (in progress)	600	70	178,830 (in progress)