Correlation Between Creep and Hot Tensile Behaviour for 2.25Cr-1Mo Steel from 500°C to 700°C. Part 2: An Assessment According to Different Parameterization Methodologies

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ABSTRACT

The criteria of equivalence between hot tensile data and creep data is assessed by the analysis of an extensive set of results obtained on 2.25Cr-1Mo steel, from 500°C to 700°C according to five traditional methodologies of creep data parameterization. Basically, it is considered that the time taken to reach the ultimate tensile stress, corresponds to a failure time which is equivalent to the rupture time in creep testing. This idea permits that hot tensile data and creep data are plotted together in the same Log(stress) versus Log(rupture time) diagram, with good compatibility with each other. An analysis is made on the Log(rupture time) versus temperature and Log(rupture time) versus inverse temperature, as recommended for selecting the more adequate parameterization method for the results. The analysis show good consistency of the hot tensile results with the creep rupture data in the 5 parameterization procedures, with less scatter in the Manson-Haferd and Orr-Sherby-Dorn analysis.

Keywords: Cr-Mo ferritic steels, creep rupture, hot tensile test data, parametric extrapolation techniques.

1 INTRODUCTION

Since the introduction of the first parameterisation method proposed by Larson and Miller \cite{1}, several methodologies appeared, based on different phenomenological hypothesis of the creep behaviour of materials \cite{2-6}. These classical methods take in consideration not only the parametric analysis of the rupture time, but also the time to reach a certain deformation level and sometimes also the minimum creep rate \cite{7}. A general evaluation of the potentialities of the several parameterisation techniques was accomplished in an international conference on the subject, in 1979 \cite{8}. In order to minimize the constraints imposed by the initial choice of a certain method, the Minimum Commitment Method (MCM) was proposed to give a larger flexibility to the parametric analysis of creep data \cite{8}. In general, none of the methods have a consistent physical basis, and the apparent success obtained with the use of a certain procedure happens from its applications in circumstantial conditions, as demonstrated by Pink \cite{9}. The method of Larson-Miller, for example, shows better consistency with the deformation processes occurring at low temperatures and offers better results in the extrapolation of this kind of data. The method of Manson Haferd, doesn't present any physical meaning, but coincidentally describes the complex pattern of deformation controlled by several mechanisms, being more reliable for predictions of data generated at higher temperatures.

All these methods were proposed to analyse specifically creep testing data. There is no mention in the literature of the use of hot tensile testing data for analysis by the same procedures.

A consistent equivalence was observed to exist between hot tensile data and creep data for 2,25Cr-1Mo steel, as described in Part 1 of this work. This article brings a further confirmation for this concept, with the application of various parameterization procedures from the traditional methodologies both to creep data and hot tensile data in the same material.

2 METHODOLOGY

Information about the material origin, its chemical composition, metallurgical condition, etc. was presented in Part 1 of this work. Details about testing techniques, equipments, testing conditions used for the tensile tests and creep tests were also presented in the same article. Twenty five constant strain rate tests were carried out in an servo-hydraulic model 8802 INSTRON machine, at 500°C, 550°C, 600°C, 650°C and
700°C, using the following crosshead speeds: 0.01 – 0.25 – 1.0 – 5.0 and 20 mm/min. Fifty creep tests were carried out in 9 temperatures levels, namely: 500°C, 525°C, 550°C, 575°C, 600°C, 625°C, 650°C, 675°C and 700°C, with 17 levels of stress, varying from 51 MPa to 414 MPa, with rupture times varying from 2 to about 1300 hours.

In this work, six methods of parameterization were considered in the analysis of the high temperature data:

The methods of Larson-Miller, Orr-Sherby-Dorn, Goldhoff-Sherby and White-Le May, are identified by the analysis of the pattern of the isostress lines in plots of Log(tr) x 1/T, in the following way:

a) Larson-Miller: Assumes the convergence of the isostress lines in a point located in the Log (tr) axis equal to \(-C\), being the parameter given by:

\[ \text{PLM} = T \left( C + \log(\text{tr}) \right) \] (1)

b) Orr-Sherby-Dorn: Is based on the parallelism of the isostress lines, with slope equal to \(A\), being parameter given by:

\[ \text{POSD} = \log(\text{tr}) - \frac{A}{T} \] (2)

c) Goldhoff-Sherby: Presupposes the convergence of the isostress lines in a point with coordinates \([1/\text{Ta}, \log(\text{ta})]\) located below the region of experimental data, being the parameter given by:

\[ \text{PGS} = (\log(\text{tr}) - \log(\text{ta})) / (1/T - 1/\text{Ta}) \] (3)

d) White-Le May: Assumes the convergence of the isostress lines in a point with coordinates \([1/\text{Tw}, \log(\text{tw})]\), above the region of experimental data, being the parameter given by:

\[ \text{PWL} = (1/T - 1/\text{Tw}) / (\log(\text{tr}) - \log(\text{tw})) \] (4)

The methods of Manson-Haferd and Manson-Succop, on the other hand, are identified by the analysis of the pattern of the isostress lines in plot Log(tr) x T, in the following way:

e) Manson-Succop: Is based on the parallelism of the isostress lines, with slope equal to \(B\), being the parameter given by:

\[ \text{PMS} = \log(\text{tr}) + B \cdot T \] (5)

f) Manson-Haferd: Presupposes the convergence of the isostress lines in a point with coordinates \([\log(\text{tm}), \text{Tm}]\), above the region of experimental data, being the parameter given by:

\[ \text{PMH} = (T - \text{Tm}) / (\log(\text{tr}) - \log(\text{tm})) \] (6)

The criteria used for converting the hot tensile data into equivalent creep data, presented in Part 1 of this work, are as follows:

1. The Strain Rate of a tensile test is equivalent to the Minimum Strain Rate in a creep test.
2. The Ultimate Stress in a tensile test is equivalent to the Applied Stress in a creep test.
3. The Time of occurrence of the Ultimate Stress (onset of necking) is equivalent to the Rupture Time in a creep test.

3 RESULTS AND DISCUSSION

Figure 1 shows the variation of stress with rupture time, both for the creep testing data and for the hot tensile data according to the conversion rules mentioned previously. The compatibility of the tensile results with the creep results is remarkable, as already discussed in Part 1 of this work.
Figures 2a and 2b show the plots of $\log(tr)$ versus the inverse of temperature and temperature respectively, with the linear regression fit in each of the fifteen isostress levels used for the creep tests and the points corresponding to the hot tensile data obtained in this work. The isostress line corresponding to 379 MPa was discarded for having only 2 points and showing great discrepancy with the other data. The analysis of these plots reveals that none of the conditions required by the respective methods is fully satisfied. The straight line equations are also shown in both plots, indicating the slopes of the intercepts in each case. The constants of each parameterization method were calculated from the creep rupture data only, considering that it was not possible to identify isostress lines with the hot tensile data. To perform the various analysis, it was necessary to use medium values of the involved constants, assuming a certain degree of convergence or parallelism pattern required in each case. The procedure of Manson and Mendelsohn (10) for this kind of analysis was used whenever possible. The analysis according to the White-Le May method was discarded by the impossibility of convergence of the isostress lines above the region of experimental data, as indicated in Figure 2a.
Figure 2a: Variation of Log (rupture time) with the inverse temperature for creep and CSR tensile tests.

Figure 2b: Variation of Log (rupture time) with temperature for creep and CSR tensile tests.
Figure 3 shows the three parameterization curves obtained with the analysis based on the pattern of isotress lines referring to the $\log(t_r)$ versus $1/T$ diagram (Figure 2a).

Figure 3a indicates the results of the Larson-Miller methodology. The value of $C = 21.592$ was calculated according to Manson and Mendelsohn method (10).

Figure 3b shows the Orr-Sherby-Dorn curve, where the average parallelism of the isotress lines was calculated by the Manson and Mendelsohn method (10), represented by the constant $B = 20631$.

Figure 3c shows the result of the Goldhoff-Sherby analysis, assuming a possible convergence point with coordinates $(1/T_a = 6.54 \times 10^{-4}$ and $\log(t_a) = -7.9)$, as indicated in Figure 2a.

The best result of this class of parameterization methodology is presented by the Orr-Sherby-Dorn method, and the worst result by the Goldhoff-Sherby method as evident from Figures 3b and 3c respectively. The Larson-Miller curve (Figure 3a) can also be considered as a satisfactory reference curve, having in mind that the data involve a broad range of temperatures, stresses and failure times corresponding to the two different kinds of tests.

Figure 4 shows the two parameterization curves obtained with the analysis based on the pattern of isotress lines referring to the $\log(t_r)$ versus $T$ plot (Figure 2b). The focal point in this figure was determined by the Manson and Mendelsohn analysis. Figure 4a and Figure 4b indicates the results of the Manson-
Haferd and the Manson-Succop analysis, respectively. The best result for this class of methodology corresponds to the Manson-Haferd analysis, as evident from Figure 4b.

**Figure 4:** The parameterisation curves for creep and CSR tensile data based on the Log (tr) versus T diagram: a) Manson-Haferd; b) Manson-Succop.

In all cases, the worst result correspond to the Goldhoff-Sherby method. The best result was obtained with the Manson-Haferd analysis which presented a value of $R^2 = 0.9927$, followed by the Orr-Sherby-Dorn ($R^2 = 0.9871$) and to the Manson-Succop methods ($R^2 = 0.9836$). The reason for the good performance of the Manson-Haferd analysis may be due the range of high temperatures used for testing the material, as pointed out by Pink [9]. The good performance of the Orr-Sherby-Dorn method is certainly related to the good fit of the Monkman-Grant relationship to the creep and hot tensile results, as described in Part 1 of this work.

The important fact, within the objectives of the present work, is that the hot tensile results have shown very good compatibility with the creep results, for all the parameterization methods investigated, what is a further confirmation of consistency in the criteria adopted for converting tensile results to creep results.

The parameterized hot tensile data have also shown a considerable region of overlap with the creep data, with their lowest stress points extending notably into the range of the creep results in each parametric curve. The final point of the hot tensile data, with the highest parameter value, correspond to the tensile test at 700°C with a crosshead speed of 0.01 mm/min, which attained its maximum stress at only 4300 s (1.19 h).

Considering that a good result was obtained for the variation of the minimum creep rate with rupture time according to the Monkman-Grant relation, as mentioned in Part 1 of this work, an attempt was made to express each of the parameterization curves using the conversion of rupture time to minimum creep rate, given by the Monkman-Grant constant. Figure 5 shows that for the present creep results: $\dot{\varepsilon}_{\text{min}}, \text{tr} = 0.0457$ and therefore: $\text{tr} = 0.0457/\dot{\varepsilon}_{\text{min}}$. 
Figure 5: Variation of the minimum creep rate with the rupture time in creep tests, plotted together with the strain rate and time for occurrence of the ultimate stress in the constant strain rate tensile tests.

Figures 6a, 6b, 6c and 7a, 7b show the parameterization curves obtained using the minimum creep rate data from both the creep tests and the CSR tensile tests, using the previously mentioned procedures of analysis given by Figures 2a and 2b respectively. The results are very similar to those obtained with the analysis considering the rupture times. The best result was again given by the Manson-Haferd method ($R^2 = 0.9915$) followed by the Orr-Sherby-Dorn ($R^2 = 0.9872$) and the Manson-Succop and Larson-Miller methods ($R^2 = 0.9813$).
Goldhoff-Sherby analysis using the Minimum Creep Rate data

\[ P = \left( \log \left( \frac{0.0457}{\varepsilon_{\text{min}}} \right) - \log \tau_a \right) / \left( \frac{1}{T} - \frac{1}{T_a} \right) \]

with \( \log \tau_a = -7.9 \) and \( 1/T_a = 6.54x10^{-4} \)

CSR tensile data

\( y = 5.85E-14x^3 - 6.07E-09x^2 + 9.56E-05x + 2.25E+00 \), \( R^2 = 0.9652 \)

Manson-Haferd analysis using the Minimum Creep Rate data

\[ P = \left( T - 364.521 \right) / \left( \log \left( \frac{0.0457}{\varepsilon_{\text{min}}} \right) - 15.963 \right) \]

CSR tensile data

\( y = 6.66E-05x^3 - 8.51E-03x^2 + 2.89E-01x - 2.80E-01 \), \( R^2 = 0.9915 \)

Manson-Succop analysis using the Minimum Creep Rate data

\[ P = \log \left( \frac{0.0457}{\varepsilon_{\text{min}}} \right) + B.T \], with \( B = 0.02519 \)

\( y = -4.54E-04x^3 + 1.48E-02x^2 - 9.61E-02x + 2.27E+00 \), \( R^2 = 0.9813 \)

Figure 6: The parameterisation curves for minimum creep rate using creep and CSR data based on the Log (\(\tau\)) versus 1/T diagram and the Monkman-Grant relation:
- a) Larson-Miller;
- b) Orr-Sherby-Dorn;
- c) Goldhoff-Sherby.

Figure 7: The parameterisation curves for minimum creep rate using creep and CSR data based on the Log (\(\tau\)) versus 1/T diagram and the Monkman-Grant relation:
- a) Manson-Haferd;
- b) Manson-Succop.

4 CONCLUSIONS

The conversion of constant strain rate tensile data to creep data, according to the criteria established in this work, has also shown to produce consistent results for 2.25Cr-1Mo steel, considering five parameterization methodologies.

The present assessment indicates also that hot tensile data can be used as a very helpful complement in the determination of parameterization curves for creep data.
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6 REFERENCES


