

Correlation between creep and hot tensile behaviour for 2.25Cr-1Mo steel from 500°C to 700°C

Part 1: An Assessment According to usual Relations Involving stress, temperature, strain rate and Rupture Time

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ABSTRACT

Hot tensile and creep tests were carried out on 2.25Cr-1Mo steel at 9 temperature levels between 500°C and 700°C, using 5 different crosshead speeds, namely: 0.01 – 0.25 – 1.0 – 5.0 and 20 mm/min, and 17 levels of stress for creep from 34 to 414 MPa. The experimental work involved the analysis of data from 30 hot tensile tests and 50 constant load creep tests, with rupture times varying from 2 to about 1300 hours. Each of these set of data were analyzed separately according to their own methodologies, but an attempt was made to find a correlation between them. A new criteria is proposed for converting hot tensile data to creep data, which makes possible the analysis of the two kinds of results according to the Norton, Zener-Hollomon, Arrhenius and Monkman-Grant relations. The results shows remarkable compatibility, indicating consistent transition from the region of power-law to exponential creep behaviour.

Keywords: Cr-Mo ferritic steels, creep data, hot tensile data, strain rate sensitivity, Norton relation, Monkman-Grant relation.

1. INTRODUCTION

The tensile properties of metallic materials at high temperatures are in general greatly affected by the strain rate. Therefore, it is important the specification and control of this variable during the tests. The ASTM E-21 standard [1] specifies that a strain rate of $0.005 \pm 0.002 \text{ min}^{-1}$ must be used at the start of the test and during yielding, and that it can be increased to $0.05 \pm 0.01 \text{ min}^{-1}$ after yielding. However, depending on the sensitivity that the strength of the material has with temperature and strain rate, the simple accomplishment of this recommendation may lead to a limited evaluation of the material performance.

Previous studies carried out on 2.25Cr-1Mo steel have shown that the yield stress, ultimate stress, final elongation and area reduction are strongly dependent on the strain rate and temperature levels used in hot tensile tests [2]. A correlation was established for the evolution of the strain hardening ($\sigma = K' \cdot \epsilon^n$) and the sensitivity of stress with strain rate ($\sigma = C' \cdot \dot{\epsilon}^m$) parameters in the region of uniform plasticity of the material [3].

An extensive series of constant load creep data was further generated in a broad range of stress and temperature in the same material, which enabled the determination of parameters in relations derived from: Norton, Arrhenius, Monkman-Grant and Creep Strength versus Rupture Time diagrams [4]. These data were also analysed according to different procedures of the traditional parameterization methodologies [5].

It is noticed that very scarce information is found in the literature relating hot tensile test results with high temperature creep results on a quantitative basis. In a tensile test it is possible to choose arbitrarily the crosshead speed (or strain rate) and the temperature level to obtain definite values of ultimate tensile stress at maximum uniform strain levels which the material can withstand under this condition. On the other hand, in a creep test one is free to choose the applied stress and temperature levels to obtain a specific minimum creep

rate and rupture time values which the material can also afford under such condition. Perhaps, a correlation between the two test modalities have not been explored yet due to the difficulty in associating results which are produced under very distinct experimental conditions using different kinds of equipment. However, tensile results and creep results are certainly different manifestations from the same reality which is the mechanical behaviour of the material, and an equivalence could be established provided an adequate correspondence is made between both situations.

This work presents results on further analysis carried out on the CSR (constant strain rate) tensile test and creep data previously reported on 2.25Cr-1Mo steel [2, 3, 4, 5], with a view to establish a quantitative correlation between the two kinds of results, which would make possible the determination of equivalent creep data from CSR test results and vice-versa in this steel.

2. METHODOLOGY

The steel was supplied in plate form with 25.4 mm thickness, according to ASTM A 387, grade 22, in the normalized and tempered condition, with the following chemical composition: Fe – 2.09Cr – 1.08Mo – 0.097C – 0.32Si – 0.50Mn – 0.007P – 0.002S – 0.03Ni – 0.01Cu – 0.05Al. Metallographic analysis indicated the presence of 30% bainite and 70% ferrite.

The specimens for the CSR tests and creep tests were extracted from the rolling direction. A gauge length $L_0 = 25$ mm and an initial diameter $d_0 = 6,25$ mm were used for all specimens.

The constant strain rate tests were carried out in a servo-hydraulic 8802 model INSTRON machine, at room temperature (25°C), 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. In this way, thirty CSR tensile tests were produced with a total variation of 3 orders of magnitude in strain rate.

The creep tests were carried out at constant load, according to ASTM E139 [6], using a set of 10 creep machines model STM-MF 1000. Information about this equipment and testing techniques appeared in previous publication [7, 8]. The elongation of the specimens was followed with creep extensometers having Transtek LVDT transducers from, model DCDT 0243-000. The readings from the transducers were collected by a Fluke Data Logger, model Hydra 2635A series II, using a scan rate of 6 readings / h. The 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 applied stress, varying from 34 MPa to 414 MPa, so that fifty creep tests were produced with rupture times varying from 2 to about 1300 hours.

All the stress, strain and strain rate values mentioned in this work correspond to nominal (or engineering) values of these parameters, i.e. they are based on the initial gauge length and initial cross-sectional area of each specimen. This procedure was adopted since the creep tests and hot tensile tests were performed in the constant load and constant crosshead speed modes respectively. Although it is recognized that true stress and strain should be used in plastic deformation behaviour analysis and that *constant stress* creep tests and *true constant strain rate* hot tensile tests should be employed, the present analysis represents a first attempt to establish a correlation between both kinds of tests as they are more widely carried out in practice.

A series of flexural resonance tests were also carried out for the determining the variation of the dynamic Modulus of Elasticity of the material with temperature, using a system consisting of a HP 33110A wave generator, a HP 54603B oscilloscope and a Advantech PCL-818H A/D conversor. The tests were carried out on 12 temperature levels from 25°C up to 700°C.

3. RESULTS AND DISCUSSION

Figure 1a shows typical stress versus strain curves obtained in the constant crosshead speed tests at the different temperatures with the lowest crosshead speed ($V_T = 1$ mm/min, $\dot{\epsilon} \sim 7 \times 10^{-6} \text{ s}^{-1}$) used in this work. It is noticed that the point of maximum load is progressively displaced to lower stress and lower strain levels, as the temperature is raised. The same behaviour was observed for the stress versus strain curves obtained at the other strain rates.

It is generally accepted that necking starts at the point of load instability, i.e. the point of maximum load in a CSR tensile test [9]. A study of the variation of the strain hardening exponent (n') and the strain rate sensitivity exponent (m'), as well as the variation of the yield stress, ultimate stress, and ultimate uniform

strain, with temperature and strain rate was presented in a previous publication [3]. All the details of this work have also been published recently [10].

Figure 1b. shows a set of typical creep curves of the material at the same temperature level (600°C) and different stresses. It is noticed that the primary stage is very short and that the minimum creep rate happens at low strain levels, with tertiary stage having a predominant contribution during the creep process in this class of material. This seems to be a typical behaviour of this class of materials, as reported by many investigators [11, 13]. Systematic observation made during this work on specimens interrupted at various points during creep have confirmed the fact that necking starts very late in tertiary stage, at the very final portion of the creep curve where the strain rate increases drastically just prior to failure [11].

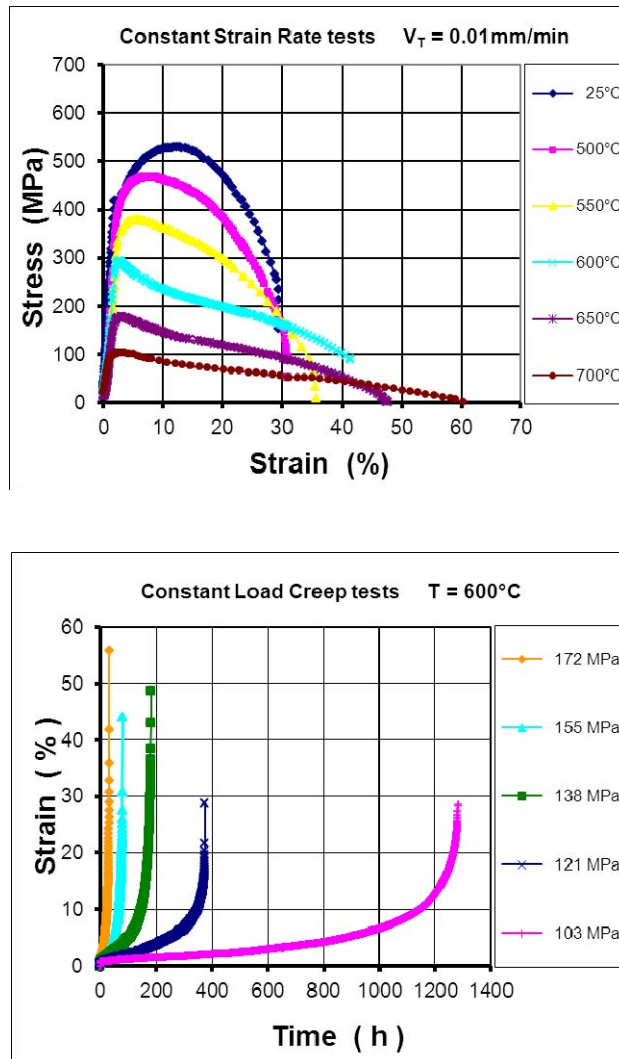


Figure 1: a) Typical Constant Strain Rate tensile testing curves at a fixed crosshead speed and different temperatures. b) Typical Constant Load Creep testing curves at a fixed temperature and different stresses.

An analogy between a CSR tensile test and a creep test can be established considering that during a CSR tensile test the temperature and strain rate are arbitrarily made constant to obtain the stress history of the material whilst during a creep test the temperature and stress are arbitrarily made constant to obtain the strain rate history of the material. In the tensile test the mechanical strength capability is attained at the point of load instability, with the onset of necking, and in the same way, during a creep test the mechanical strength of material is maintained until the onset of necking, i.e. very close to the specimen rupture time.

With this analogy the equivalence between both kinds of test was established in this work, according to the following criteria:

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

These rules were applied to convert the CSR tensile results [4, 5] to “creep” data, as an attempt to plot them together with the real creep data obtained in the same material [2, 3].

Figure 2 shows the variation of the minimum creep rate with stress, at the various temperature levels considered in this work, together with the equivalent “creep” data obtained from the CSR tests as mentioned above. The agreement of the CSR tensile results with the creep data is evident. The slope of each curve in the creep region corresponds to the stress exponent (n value) of the Norton law ($\dot{\epsilon}_s = A \cdot \sigma^n$) which decreases with temperature. As the stress increases, the slope of the curves in the tensile test region corresponds to the inverse of the strain rate sensitivity exponent ($1/m'$ value). According to a previous publication, as the temperature increases the values of m' increases and n decreases [3]. Assuming $\sigma = C' \cdot \dot{\epsilon}^{m'}$, then $\dot{\epsilon} = A \cdot \sigma^{1/m'}$, therefore $n = 1/m'$, as the experimental data suggests.

Figure 2 includes the equivalent creep data referring to the tensile data at room temperature. The data show a very high n value with an indication of very low m' value, i.e. low possibility of occurrence of creep on extrapolation of the curve to lower stress levels at room temperature, as observed experimentally. It is also noteworthy that the sequence of data at each temperature level shows a clear evidence of the power-law breakdown leading to exponential creep at the higher stress levels [12].

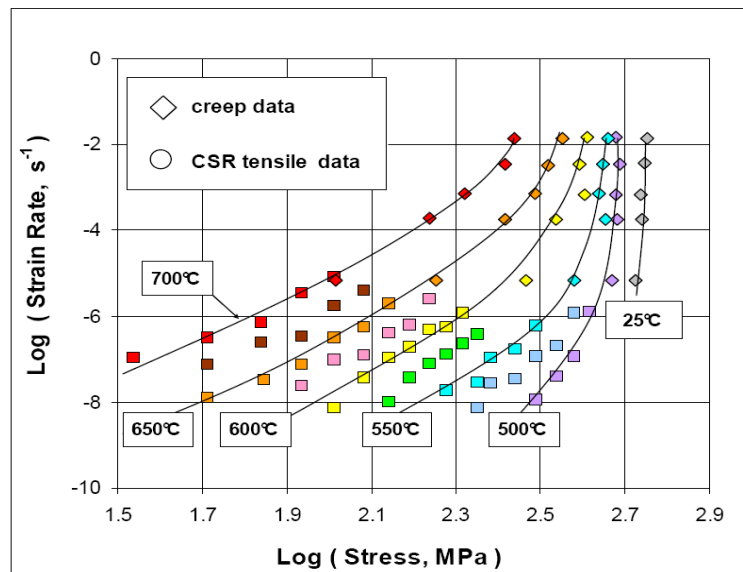


Figure 2: Variation of the minimum creep rate with the applied stress in creep tests, plotted together with the ultimate tensile stress and the strain rate data in the constant strain rate tensile tests.

Figure 3 shows the variation of the minimum creep rate with the inverse temperature, for the various creep stress levels investigated in this work, according to an Arrhenius type diagram. The hot tensile results are represented by open circles in the upper part of the diagram and they have a label identification for the ultimate stress reached in each CSR test. Again a good agreement is obtained with the creep data which are organized in their respective isostress lines. The figure points out the compatibility between both class of results along five isostress lines, namely: 103 MPa, 172 MPa, 241 MPa, 310 MPa and 379 MPa. Apparent activation energies could be derived from the slopes of such isostress lines, including both creep and tensile stress results ($\dot{\epsilon}_s = B \cdot e^{-Q/RT}$). It is apparent in Figure 3 that, for the range of stress and temperature explored in the creep tests (52 to 379 MPa), a common slope could be attributed to the CSR and creep data, which means a common activation energy for both deformation processes.

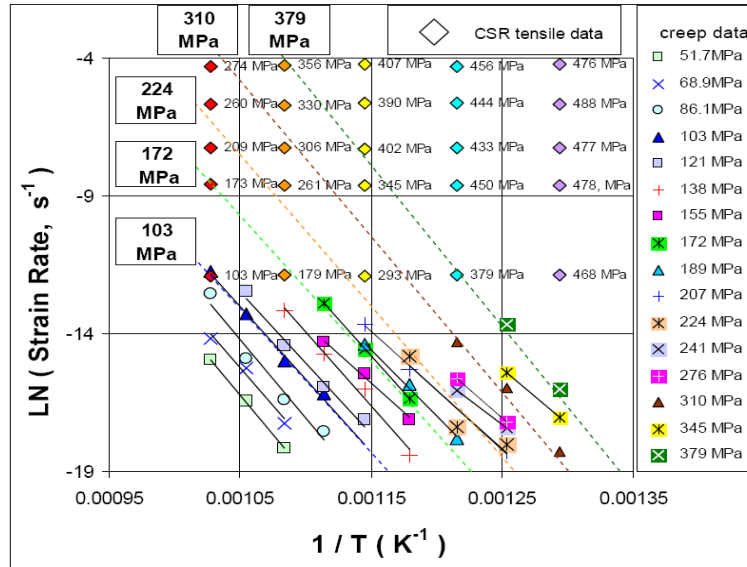


Figure 3: Variation of the minimum creep rate with the inverse temperature in creep tests, plotted together with the strain rate and inverse temperature data in constant strain rate tensile tests.

Figure 4 shows the variation of the minimum creep rate with rupture time for the creep data generated in this work, and the CSR tensile data converted to “creep data” as mentioned previously. The set of creep data was observed to follow a Monkman-Grant relationship ($\dot{\epsilon}_s \cdot t_r^m = K$, with $m \sim -1$), in excellent agreement with results mentioned by other investigators for 2.25Cr-1Mo steel, as pointed out by Viswanathan [13]. The regression lines mentioned by this author are also shown in Figure 4. The agreement of the CSR tensile data with the creep results, according to the Monkman-Grant fit is evident. For each strain rate level, the CSR “rupture time” data are inversely related with temperature, a characteristic which is more evident in the CSR tensile results, as the strain rate is the independent variable in these tests. For the creep data it is more difficult to detect this effect since the independent variable in the test is the applied stress. Therefore, the scatter observed on the creep data in this kind of plots could be of the same nature as observed for the CSR results. It is also observed that the points which present greater deviation from the Monkman-Grant borderlines are those referring to the room temperature tensile results, which have no correspondence in the creep data region.

Figure 5 shows the variation of the applied creep stresses with rupture time, at the various temperature levels investigated in this work plotted with de equivalent CSR “creep” results. Again the agreement of the CSR tensile results with the creep data is remarkable. The diagram includes the equivalent creep data referring to the CSR tensile data at room temperature, and it is very suggestive that it bears a great resemblance to pattern of data shown Figure 2. This seems consistent with the validity of the Monkman-Grant relation, represented in Figure 4, which establishes an inverse variation of the strain rate with the rupture time.

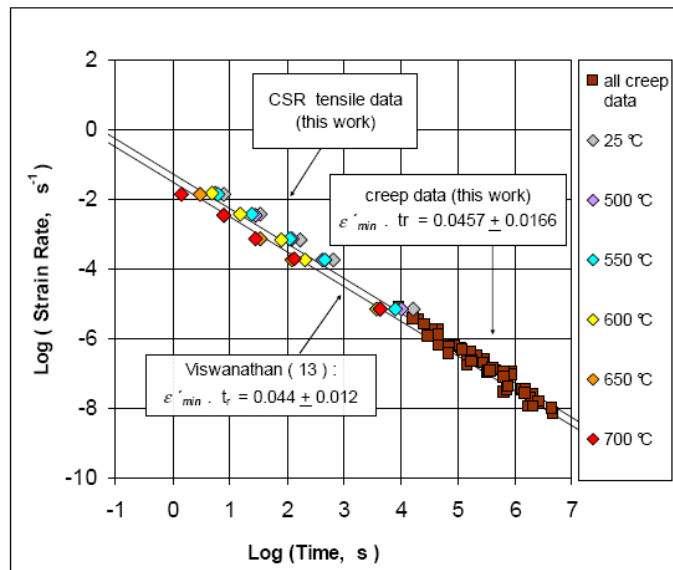


Figure 4: Variation of the minimum creep rate with the rupture time in creep tests, plotted together with the strain rate and time for occurrence of the ultimate stress in the constant strain rate tensile tests.

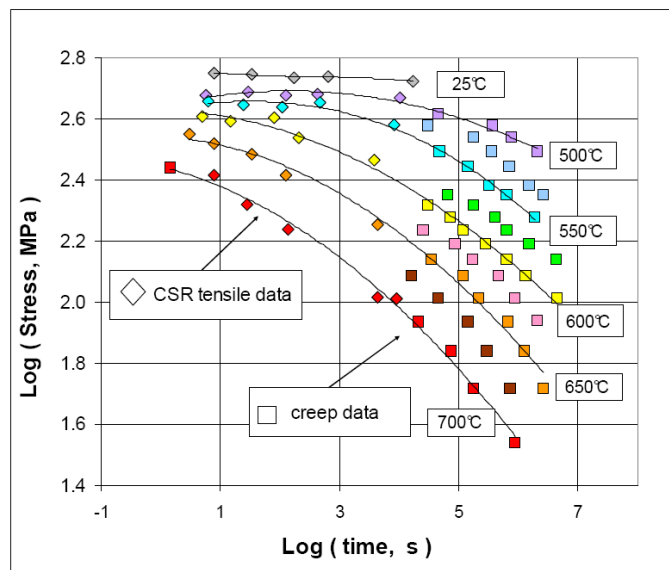


Figure 5: Variation of the stress with rupture time in creep tests, plotted together with the ultimate tensile stress and the time for its occurrence in the constant strain rate tensile tests.

Figure 6 shows the results obtained with the resonance test for determination of the dynamic Modulus of Elasticity of 2.25Cr-1Mo steel. The results are compared with measurements of the Young Modulus obtained during the hot tensile tests at $V_T = 0.25 \text{ mm/min}$, and data reported by Maruyama *et al.* for 2.25Cr-1Mo steel [14] and Frost and Ashby [15] for 1Cr-Mo-V steel. The dynamic data obtained in this work shows better agreement with the results reported by Frost and Ashby.

A careful analysis was carried out on the variation of the minimum creep rate with stress, to verify the possibility of expressing the data according to the relation [11]:

$$\dot{\epsilon}_{min} = A \left(\frac{\sigma}{E} \right)^n \cdot \exp\left(-\frac{Q_f}{RT}\right) \quad (1)$$

where A is a constant depending on the material, $\dot{\epsilon}_s$ is the steady-state or minimum creep rate, E the Elastic Modulus at the temperature, n the stress exponent and R the gas constant.

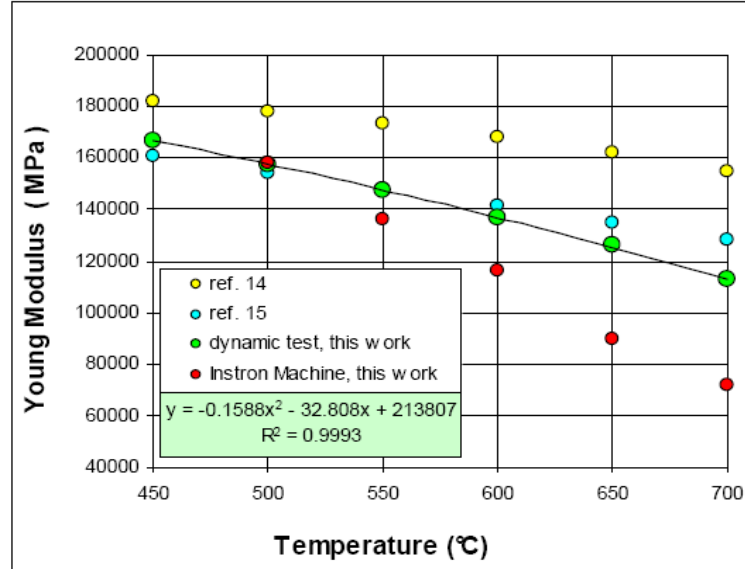


Figure 6: Variation of the Young Modulus with Temperature, for 2.25Cr-1Mo steel determined in this work by dynamic and static tests, compared with data from Murayama *et al* [14] for 2.25Cr-1Mo and Frost and Ashby [15] for 1Cr-Mo-V steels.

A plot of $\text{Log}(\dot{\epsilon}_s)$ versus $\text{Log}(\sigma/E)$ showed that, except for some lower stress points at 700°C, 675°C and 650°C and some higher stress points at 500°C and 525°C, most of the data at each temperature level could be well expressed by straight lines with a common slope $n = 6.1$. A plot of the intercepts of these straight lines with $1/T$ revealed a value of $Q = 345 \text{ kJ/mol}$ as the best value for expressing the creep behaviour of the material, so that the following expression was found to express the data in an intermediate stress range:

$$\dot{\epsilon}_{min} = 8.558 \times 10^{31} \left(\frac{\sigma}{E} \right)^{6.11} \cdot \exp\left(-\frac{345000}{RT}\right) \quad (2)$$

Figure 7a shows the variation of the Log (minimum creep rate) with Log (stress), where the straight lines correspond to the prediction by Equation 2, and the interrupted lines express the deviation of some data points from the predicted behaviour, as mentioned previously.

If Equation (1) holds, it is possible to express the creep data by the Zener-Hollomon Parameter (Z), i.e.:

$$Z = \dot{\epsilon}_{min} \cdot \exp\left(\frac{Q_f}{RT}\right) = A \left(\frac{\sigma}{E} \right)^n \quad (3)$$

Figure 7b shows all creep data plotted as Log (Zener-Hollomon Parameter) versus Log (normalized stress). It is evident that the parameter was very adequate to make the data collapse in a single reference curve, with an intermediate region, $6 \times 10^{-4} < \sigma / E < 2 \times 10^{-3}$ having a Norton exponent $n = 6.1$.

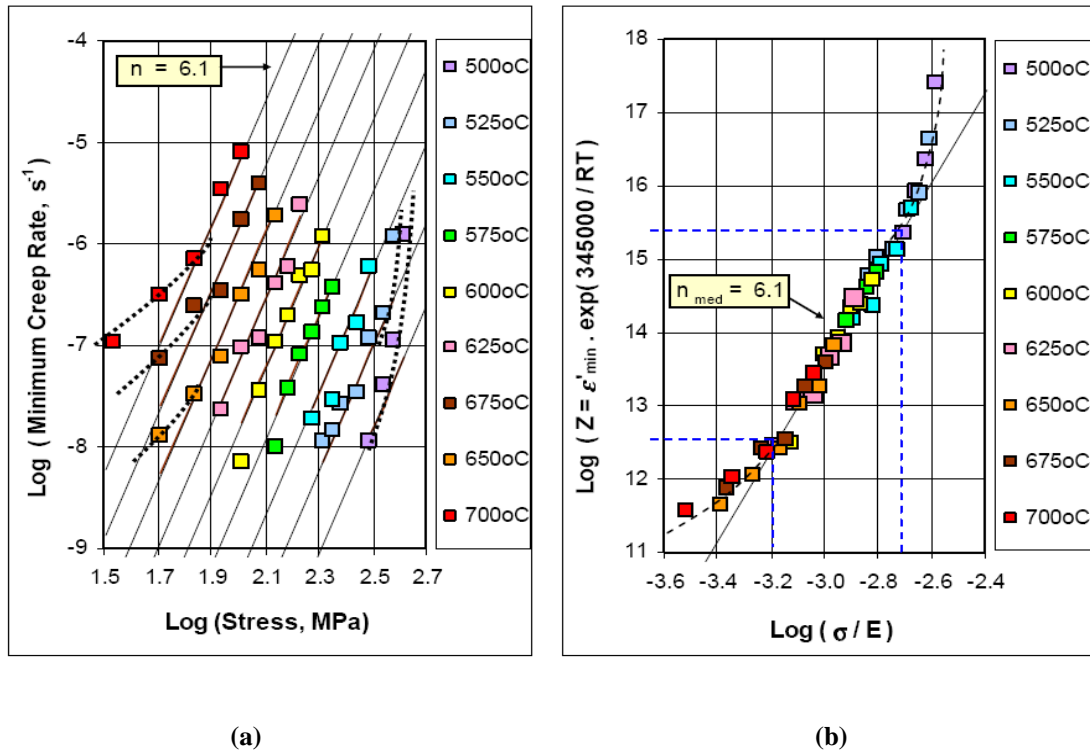


Figure 7: Analysis of the variation of the minimum creep rate with stress: a) Identification of common slopes with the same n value through the data; b) Rationalization of the data using the Zener-Hollomon Parameter.

Figure 8 shows the creep data and the equivalent “creep data” from the CSR results plotted together in the same fashion of Figure 7b. The agreement of both sets of results with each other is remarkable. Most of the CSR data are beyond the region where the power-creep law breaks down. However, some of the lower stress points at 700°C and 675°C shows very good agreement with the creep data in the intermediate creep stress region where n = 6.1.

As a good correlation was obtained for creep according to the Monkman-Grant relation (Figure 4), an attempt was made to express the data by a combined parameter involving the Zener-Hollomon Parameter and the Monkman-Grant relation, here named Zener-Monkman Parameter (ZM):

$$Z = \dot{\epsilon}_{min} \cdot \exp\left(\frac{Q_f}{RT}\right) = A \left(\frac{\sigma}{E}\right)^n = \left(\frac{K}{c_r}\right) \cdot \exp\left(\frac{Q_f}{RT}\right) = ZM \quad ((4))$$

Figure 9 shows the variation of Log (ZM) versus Log (normalized stress) for both the creep data and the CSR transformed “creep” data. Again the agreement is excellent, with an intermediate stress region similar to that of Figure 8, having a slope slightly greater than 6.1. It is also remarkable that some of the lower stress points at the highest temperatures (700°C and 675°C) shows also good agreement with the creep data in the intermediate creep stress region. These points correspond to the CSR test carried out at the lower crosshead speeds of 0.01 and 0.25 mm/min mainly.

Recently, the methodology of analysis using the equivalence between Hot Tensile data a Creep data has been applied to results obtained on Commercially Pure Copper, also with remarkable success [16, 17]

The present data with 2.25Cr-1Mo steel was also analysed according to different parameterization methodologies, which also confirms the good compatibility between the Hot Tensile and Creep results, for extrapolation purposes [18].

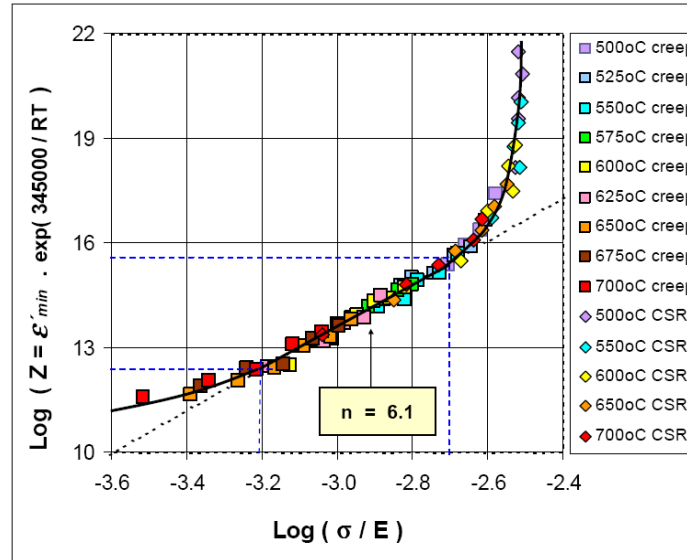


Figure 8: Variation of the Zener-Hollomon Parameter with the normalized applied stress in creep tests, plotted together with equivalent data from the constant strain rate tensile tests.

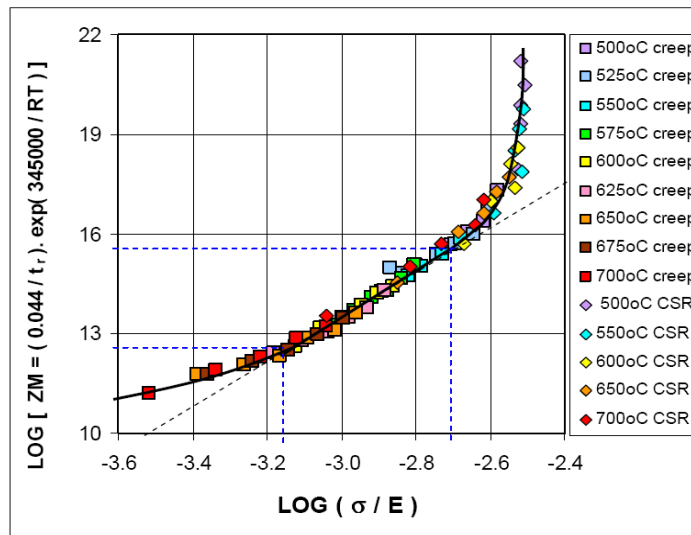


Figure 9: Variation of the combined Zener-Monkman Parameter with the normalized applied stress in creep tests, plotted together with equivalent data from the constant strain rate tensile tests.

4. CONCLUSIONS

The application of the criterion proposed in this work for converting hot tensile testing data to creep data gave results that are consistent and significant when confronted with real creep data obtained for 2.25Cr-1Mo steel, considering the main diagrams and relations suggested in the literature for analysis of creep behaviour.

The analysis involving CSR and creep tests for 2.25Cr-1Mo steel under the present conditions indicates that Hot CSR data can be converted to creep data and vice-versa according to the 3 rules established in this work, namely: i) the Strain Rate of a tensile test is equivalent to the Minimum Creep Rate in a creep test; ii) the Ultimate Stress in a tensile test is equivalent to the Applied Stress in a creep test; iii) the Time of occurrence of the Ultimate Stress in a tensile test is equivalent to Rupture Time in a creep test.

This procedure seems to have important implications and should be further explored in a sounder physical basis, with more testing for its validation on other metallic materials.

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