ON THE EQUIVALENCE BETWEEN HOT TENSILE DATA AND CREEP DATA [1]

Levi de Oliveira Bueno [2]

Abstract

A new criterion is proposed for converting hot tensile data to creep data, and vice-versa. The criterion considers basically that the peak stress, the time taken for its occurrence, and the strain rate in a constant strain rate test at high temperature is equivalent to the applied stress, the rupture time and minimum creep rate, respectively, in a creep test. These concepts have been put forward to some extent previously by other authors, but they are in this paper generalized and tested experimentally with success for two materials. A first set of constant crosshead speed hot tensile data and *constant stress* creep data on AISI 310 type stainless steel, at 700°C, was analyzed with the equivalence happening for the *true* values of stress and creep rate. A second set of constant crosshead speed hot tensile tests and *constant load* creep tests on 2.25Cr-1Mo steel at temperatures from 500°C to 700°C , using 5 different crosshead speeds, from 0.01 to 20 mm/min, and 19 creep stress levels from 34 to 448 MPa was specially programmed for this work. The analysis of both sets of data presents remarkable compatibility with each other considering the *nominal* values of stress and creep rate. The Norton diagrams indicate consistent transition from the region of power-law to exponential creep behaviour and significant similarity was observed in the Monkman-Grant, Arrhenius, Stress versus Rupture Time plots and also some Parameterization curves involving both kind of data. The results strongly indicate that hot tensile data can be converted to creep data and vice-versa.

Key words: Creep data; Hot tensile data; Strain rate sensitivity; Norton and Monkman-Grant relations.

SOBRE A EQUIVALÊNCIA ENTRE DADOS DE TRAÇÃO A QUENTE E DADOS DE FLUÊNCIA

Resumo

Propõe-se um novo critério para converter dados de tração a quente em dados de fluência e vice-versa. O critério considera basicamente que a tensão máxima, o tempo para sua ocorrência e a taxa de deformação aplicada em um ensaio com taxa de deformação constante em alta temperatura é equivalente à tensão aplicada, o tempo de ruptura e a taxa mínima de fluência, respectivamente, em um ensaio de fluência. Esse procedimento foi parcialmente sugerido por alguns autores anteriormente, porém neste artigo os conceitos são sintetizados e uma verificação experimental de sua validade é feita com sucesso para dois materiais. Um primeiro conjunto de dados de tração a quente com velocidade da travessa constante e dados de fluência a *tensão constante* no aço tipo AISI 310 a 700°C foi analisado por esse modelo. A análise indica notável equivalência entre os dois grupos de resultados considerando-se os valores reais de tensão e taxa de deformação em cada caso. Um segundo conjunto mais completo de resultados foi programado para este estudo utilizando-se o aço 2,25Cr-1Mo entre 500 e 700°C, a saber: 25 ensaios de tração a quente com 5 velocidades da tração variando de 0,01 a 20 mm/min em 5 níveis de temperatura, juntamente com cerca de 60 ensaios de fluência a *carga constante* com 19 níveis de tensão variando de 34 a 448 MPa em 9 níveis de temperatura. A análise indica uma excelente compatibilidade entre os dois grupos de resultados considerando-se os valores nominais de tensão e taxa de deformação em cada caso. Os diagramas de Norton apresentam consistente transição da região de comportamento por fluência potencial para fluência exponencial. A similaridade entre os dois tipos de dados nos diagramas de Monkman-Grant, Arrhenius, ou nos gráficos que variação da resistência a fluência com o tempo de ruptura, e também em curvas de parametrização segundo diferentes metodologias mostra-se altamente significativa. Os resultados sugerem fortemente que dados de tração a quente podem ser convertidos com segurança para dados de fluência e vice-versa.

Palavras-chave: Dados de fluência; Dados de tração a quente; Sensibilidade à taxa de deformação; Relações de Norton e Monkman-Grant.

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[1] *Technical Contribution to the 61st International Congress of the ABM, January 24-27th 2006, Rio de Janeiro – RJ – Brazil.*

[2] *Associate Professor DEMa – UFSCar, Ph.D. Materials Engineering - Rod.Washington Luiz, km.235 – 13565-905 São Carlos(SP). E-mail: levi@power.ufscar.br*

1 INTRODUCTION

The effect of strain rate during tensile testing of metallic materials at high temperatures can be of great concern for the correct specification of important parameters like the yield and ultimate tensile stress levels, as pointed out by Guest.(1) Therefore, it is important the specification and control of the level of strain rate used during the tests, as recommended by many standards. The ASTM E-21,(2) for instance, specifies that a strain rate of 0,005 ± 0,002 min^{-1} must be used at the start of the test until yielding is fully established, and that the strain rate can be increased to 0,05 ± 0,01 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 very limited evaluation of the material performance.

Previous studies carried out on 2.25Cr-1Mo steel by Bueno et al.(3) have shown that the yield stress, ultimate stress, final elongation and area reduction are strongly dependent on the strain rate and temperature ranges used in the hot tensile tests. A correlation was also established for the evolution of the strain hardening parameters ($\sigma = \mathbf{K}.\varepsilon^{n'}$) and the sensitivity of stress with strain rate parameters ($\sigma = \mathbf{C}.\dot{\varepsilon}^{m'}$) in the region of uniform plasticity of the material, as reported by Reis Sobrinho et al.(4) These results have good agreement with the data obtained by Klueh and Oakes(5) which also indicated a strong dependence of yield stress and UTS with temperature and strain rate for the same steel.

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 stress versus rupture time diagrams, as reported by Bueno and Reis Sobrinho.(6) Such data were also analysed according to different procedures of the traditional parameterization methodologies, as reported by Reis Sobrinho and Bueno.(7)

Very scarce information is found in literature relating hot tensile test results with high temperature creep results on a quantitative basis. In a hot 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 specific minimum creep rate and rupture time values which the material can also withstand under this condition. Perhaps a correlation between the two test modalities have not been explored yet because of the difficulty in associating results which are produced under very distinct experimental conditions, with also different kinds of equipment. However, hot 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 an analysis with a first set of constant crosshead speed (CCS) tensile results and constant stress creep results obtained at 700°C on AISI 310 Type stainless steel and with a second set of extensive CCS hot tensile data and constant load creep data on the 2.25Cr-1Mo steel previously mentioned, as an attempt to establish a correlation between the two kind of results. A criterion converting hot tensile data to creep data and vice-versa is proposed, which seems to be physically consistent with recent theories of creep deformation behaviour.

2 METHODOLOGY

The set of creep data on Type AISI 310 steel was generated on *constant stress* condition, at 700°C, using a set of creep machines that can perform either constant load or constant stress tests using interchangeable cams adequate for each situation, as described by Bueno[8] and Contin Jr.[9] The tensile data were also obtained at 700°C, with the following crosshead speeds: 0.001 – 0.01 – 0.25 – 1 – 5 and 20 mm/min, using an Instron machine model 1127(now upgraded to 5500R) . The material was solution treated at 1050°C for 1hour, exhibiting a fully austenitic structure with average grain size of 210μm. The hot tensile and creep specimens had gauge length L_o= 50mm and initial diameter d_o = 6 mm. The values of stress, strain and strain rate presented in this case correspond to the *true* (or *real*) values of these parameters.

The 2.25Cr-1Mo 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 hot tensile and creep tests were extracted from the rolling direction. A gauge length L_o = 25 mm and an initial diameter d_o = 6.25mm were used for all specimens. The CCS 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 – 5 and 20 mm/min. In this way, thirty CCS 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 using the same set of creep equipment mentioned previously. 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: 500ºC, 525ºC, 550ºC, 575ºC, 600ºC, 625ºC, 650ºC, 675ºC and 700ºC, with 19 levels of applied stress, varying from 34 MPa to 448 MPa, so that about 60 creep tests were produced with rupture times varying from 0.13 to about 1300 hours. All the stress, strain and strain rate values mentioned in the analysis of the 2.25Cr-1Mo steel correspond to *nomina*l (or *engineering*) values of these parameters, i.e. they are based on the initial gauge length and initial cross-sectional area of each specimen.

Figures 1a and 1b show the two kind of equipment used in this research, i.e. tensile testing machine and creep machines respectively.

3 THE CRITERION FOR TENSILE / CREEP EQUIVALENCE

It is important to mention at this stage that the criterion proposed in this work was defined on basis of simple arguments related to the nature of both kind of tests and the possible relation that they may have with the onset of the necking process. The criterion was conceived almost intuitively, based on practical experience in carrying out hot tensile and creep tests over many years with manipulation of these results trying to find some kind of reciprocity between them.

Figure 1 – Equipment used in this work: **a)** universal testing machine; **b)** Row of 10 constant stress/constant load creep machines.

An approximate similar criterion was proposed by Steen(10) some years ago to relate stress and strain rate data in creep and CSR (constant strain rate) testing. When the present criterion was defined no other information was found in literature. However, it is important to mention the work by Osgerby and Dyson,[11] which establishes an almost identical procedure for comparing both kind of data. The work of these author is important by the fact that their approach is supported by a physical model using mechanisms-based equations for creep behaviour. With their model it seems possible to predict stress trajectories as a function of strain under constant strain rate.

It is generally accepted that necking starts at the point of load instability, i.e. the point of maximum load in a CCS tensile test.[12] The onset of necking can be considered as a point of failure condition both in CCS tensile testing and creep testing, as suggested by Penny.[13]

The analogy between a CCS tensile test and a creep test was established considering that during a CCS 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 exhausted at 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:

1. *The Strain Rate of a tensile test is virtually identical to the Minimum Strain Rate in a creep test.*
2. *The Ultimate Stress is a tensile test is virtually identical to the Applied Stress in a creep test.*
3. *The Time of occurrence of the Ultimate Stress (onset of necking) is virtually identical to the rupture time in a creep test.*

These rules were applied to convert the CCS tensile results reported by Bueno et al.[3] and Reis Sobrinho et al.[4] to *"creep"* data, as an attempt to plot them together with the real creep data obtained in the same material by Bueno and Reis Sobrinho[6] and Reis Sobrinho and Bueno.[7]

4 RESULTS AND DISCUSSION

4.1. Analysis of the Type AISI 310 Data

Figure 2a shows typical conventional stress versus strain curves in CCS tensile tests at the various constant crosshead speed values and Figures 2b and 2c constant stress creep curves at different applied stress levels, at 700°C with Type AISI 310 stainless steel. Before the conversion to equivalent creep data, the conventional values of stress, strain and strain rate values were transformed in true values by the usual relations: $\varepsilon_{true} = \ln(1 + \varepsilon_{conv})$ and $\sigma_{true} = \sigma_{conv}(1 + \varepsilon_{conv})$. In Figures 2b and 2c, the strain axis of the creep curves already correspond to the true values of strain.

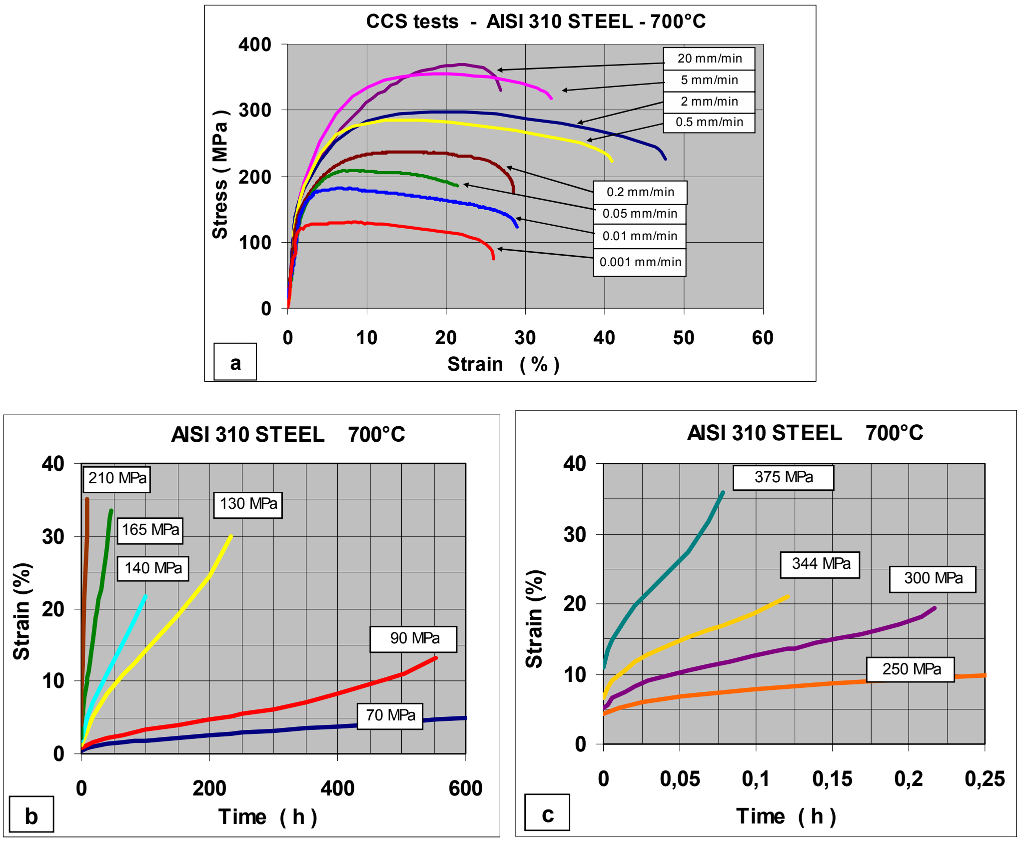

Figure 2. a) Tensile testing curves at 700°C and different crosshead speeds; **b)** and **c)** Constant stress creep testing curves at 700°C and different stresses. Material: AISI 310 Type Stainless Steel.

Figure 3 shows the variation of the applied creep stresses with rupture time, at the various temperature levels plotted with de equivalent CCS "creep" results. The agreement of the CCS tensile results with the creep data can be considered quite reasonable, having in mind the scatter that usually affects creep data.

Figure 4 presents a Norton type diagram, i.e. the variation of the minimum creep rate with the stress applied in creep tests, plotted with the true stress at maximum load and the true strain rate applied in the hot tensile tests. The creep data presents a change in the stress exponent from a value of **n**= 4.5 to **n**= 7.1 which is typical , according to various authors.[14,15] The CCS data present remarkable compatibility with the creep results in the higher stress exponent region.

Figure 5 shows the variation of the minimum creep rate with the rupture time in the creep tests, plotted with the time for ultimate stress occurrence and the true strain rates applied in the hot tensile tests. The results of three other constant stress creep tests carried out at 600, 625 and 670ºC are included in the diagram. All the creep data are well expressed by the Monkman-Grant relation ($\dot{\boldsymbol{\varepsilon}}_{min} . \mathbf{t_r}^{m} = \mathbf{K}$) with **m** ~1. The points relative to the CCS data are located slightly below the regression line, but can be considered still to exhibit good agreement with the creep results, considering also the experimental scatter normally shown by such kind of data.

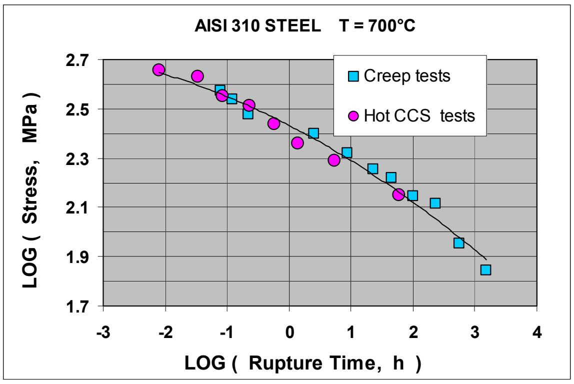

Figure 3. Variation of the stress with rupture time in creep tests, plotted with the true stress at maximum load and the time for its occurrence in the hot tensile tests.

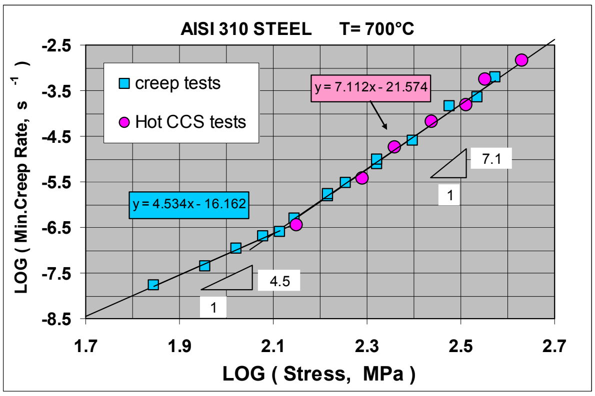

Figure 4 - Variation of the minimum creep rate with the stress applied in creep tests, plotted with the true stress at maximum load and the true strain rate applied in the hot tensile tests.

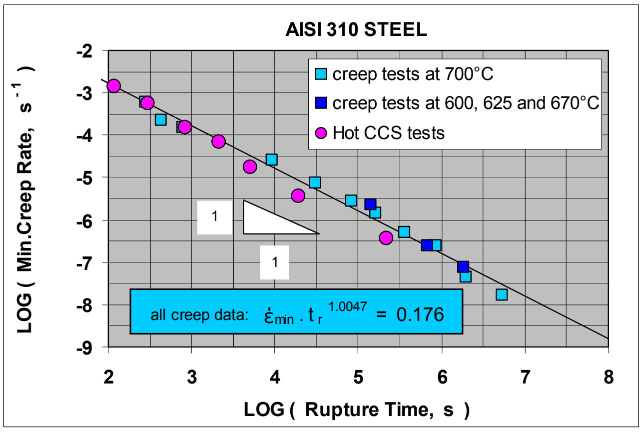

Figure 5 - Variation of the minimum creep rate with the rupture time in creep tests, plotted with the time for ultimate stress occurrence and the true strain rates applied in the hot tensile tests.

4.2 Analysis of the 2.25Cr-1Mo Data

Figure 6a shows typical conventional stress versus strain curves obtained in the CCS tests at the lowest crosshead speed ($\mathbf{V_C}$ = 0.01mm/min, $\dot{\boldsymbol{\varepsilon}}$ ~ $6.7 \times 10^{-6} s^{-1}$) and different temperatures. 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 crosshead speed values.

Figure 6b. shows a set of typical creep curves of the material in a 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 2.25Cr-1Mo steel. This seems to be a typical behaviour of this class of materials, as reported by many investigators.[16,17] Systematic observation made during this work on specimens interrupted at various points during the creep test 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.[16]

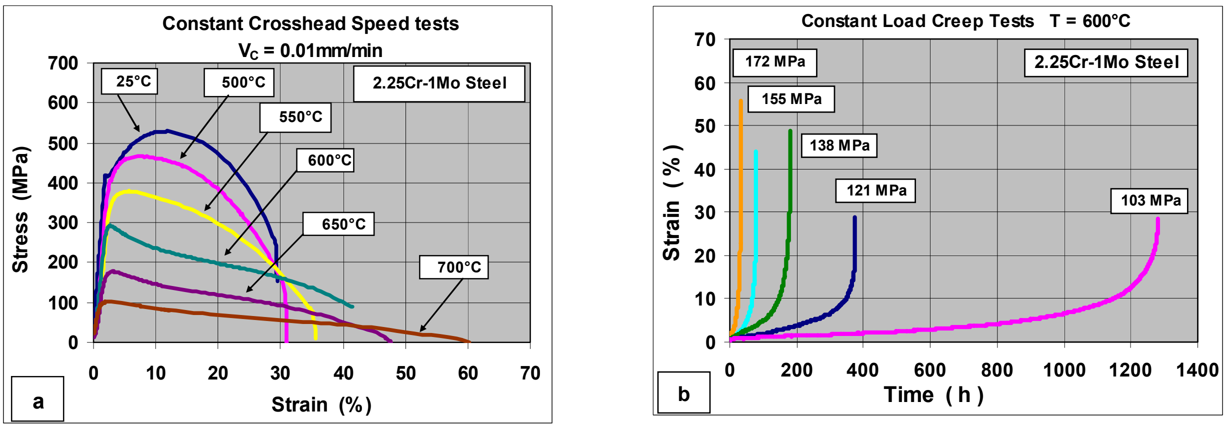

Figure 6. a) Typical tensile testing curves at a constant crosshead speed and different temperatures; **b)** Typical creep testing curves at constant temperature and different stresses - for 2.25Cr–1 Mo Steel.

Figure 7 shows the variation of the minimum creep rate with stress, in the form of Norton diagrams, at the various temperature levels considered in this work, together with de equivalent “creep” data obtained from the CCS tests as mentioned above. The agreement of the CCS 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 ($\dot{\boldsymbol{\varepsilon}}_{min} = \mathbf{A}.\sigma^{n}$) which decreases with stress and increases with temperature, as observed experimentally (Evans and Wilshire(16)). As the stress increases, the slope of the curves in the tensile test region correspond to the inverse of the strain rate sensitivity exponent (**1/m´** value). According to a previous publication (Reis Sobrinho et al (4)), as the temperature increases the values of **m´** increases and **n´** decreases. Assuming that $\sigma = \mathbf{C}.\dot{\varepsilon}^{m'}$, then $\dot{\varepsilon} \propto \sigma^{1/m'}$, therefore **n = 1/m´** , as the experimental data suggests.

Figure 7 also includes the equivalent creep data referring to the tensile data at room temperature. The data show a very high **n** exponent 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 notable 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.[14]

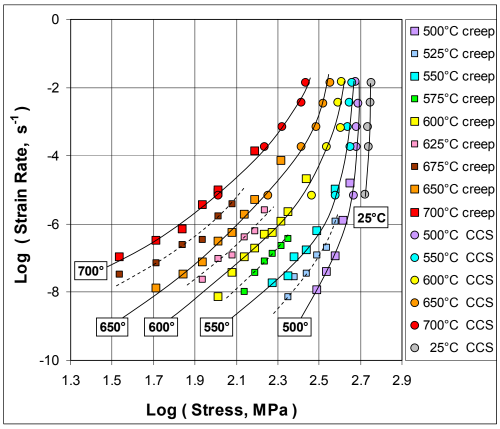

Figure 7. Variation of the minimum creep rate with the stress applied in creep tests, plotted together with the ultimate tensile stress and the nominal strain rate applied in the hot tensile tests.

Figure 8 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 figure with an identification of the ultimate stress value reached in each CCS test, in MPa. Again a good agreement is obtained with the creep data which are organized in their respective isostress lines. The compatibility between both class of results is pointed out along five isostress lines, for illustration, namely: 103, 155, 207, 310 and 379 MPa. Apparent activation energies could be derived from the slopes of such isostress lines, including both creep and tensile stress results ($\dot{\varepsilon}_{min} = B \ . \ e^{-Q/RT}$). It seems quite reasonable to assume that, for the range of stress and temperature used for the creep tests (34.5 to 448 MPa), within experimental scatter, all the iso-stress lines have the same common slope both for the CCS and creep data, which would mean a common activation energy for both deformation processes. However, it is difficult to work in iso-stress conditions with the hot tensile data. It was also observed that at the lower temperatures (550 and 500°C) the tensile data were affected by the dynamic strain aging phenomena, with the appearance of serrated flow and negative strain rate sensitivity exponents (**m´**) bringing about inversions in the variation of the yield stress and UTS values with strain rate.[3]

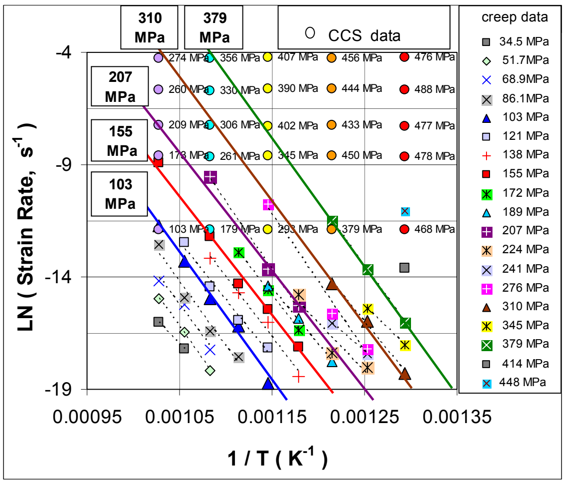

Figure 8 - Variation of the minimum creep rate with the inverse temperature used in creep tests, plotted with the inverse temperature and the nominal strain rate levels applied in the hot tensile tests. Numbers on the right hand side of round symbols are ultimate tensile stress values of each test, in MPa.

Figure 9 shows the variation of the minimum creep rate with rupture time for the creep data and the CCS tensile data converted to "creep data" according to the criterion proposed in this work. The set of creep data was observed to follow the Monkman-Grant relationship ($\dot{\boldsymbol{\varepsilon}}_{min}.\mathbf{t_r}^{\mathbf{m}} = \mathbf{K}$, with **m** ~1), in excellent agreement with results mentioned by other investigators for 2.25Cr-1Mo steel, as pointed out by Viswanathan.(17) The regression lines mentioned by this author are also shown in the figure. The agreement of the CCS tensile data with the creep results, along the Monkman-Grant linear regression fit is evident. It is interesting that even the room temperature tensile results (at 25°C) which were converted to creep show excellent agreement with the high temperature results. For the CCS tensile results, the time data at each strain rate level are clearly observed to be inversely related with temperature. This pattern is more evident in the case of the 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. It seems that the scatter observed on the creep data in this kind of plot could be of the same nature as that for the CCS results. It is also apparent 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 10 shows the variation of the applied creep stresses with rupture time, at the various temperature levels investigated in this work plotted with de equivalent CCS "creep" results. Again the agreement of the CCS tensile results with the creep data is remarkable. The diagram includes the equivalent creep data referring to the CCS tensile data at room temperature, and it is very suggestive that it bears a great resemblance to the pattern of data shown Figure 7. This seems consistent with the validity of the Monkman-Grant relation, represented in Figure 9, which establishes an inverse variation for the strain rate with rupture time.

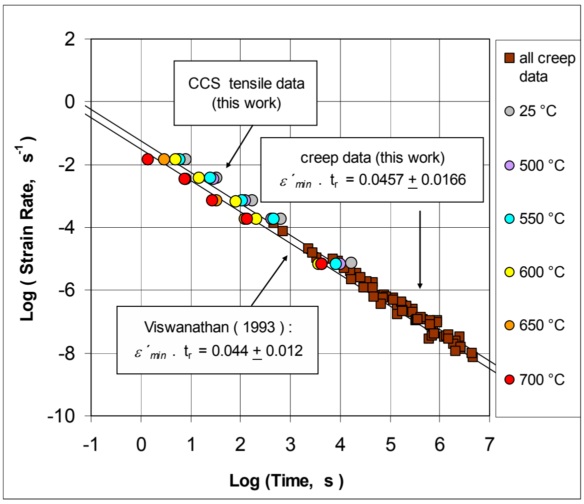

Figure 9 - Variation of the minimum creep rate with the rupture time in creep tests, plotted with the time for ultimate tensile stress occurrence and the nominal strain rates applied in the hot tensile tests.

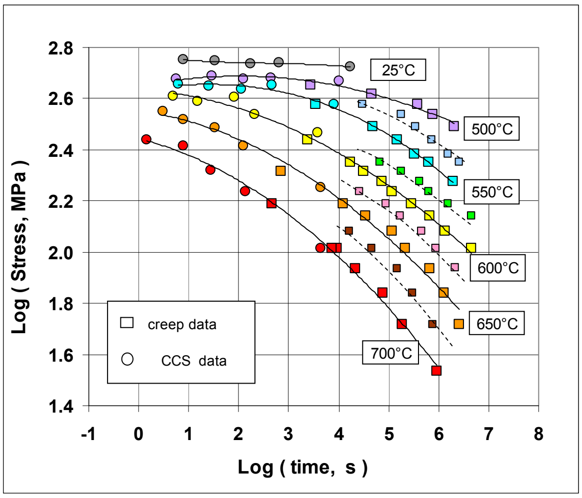

Figure 10 - Variation of the stress with rupture time in creep tests, plotted with the ultimate tensile stress and the time for its occurrence in the hot tensile tests.

Other aspects of compatibility between the hot tensile and creep testing data on 2.25Cr-1Mo has recently been presented by Bueno,[18] involving equivalence in parameterization analysis for minimum creep rates by the Zener-Hollomon method, and also in parameterization analysis for rupture time by different methods, like Larson-Miller, Orr-Sherby-Dorn, Manson-Haferd, and others.

5 DISCUSSION

A suggestion was put forward by Steen[10] that constant strain rate data could be used as convenient substitute for the time-consuming creep results. Contrary to Steen,[10] however, Osgerby and Dyson[11] consider exactly the opposite option, i.e. that creep testing can substitute hot tensile testing economically in many situations by the use of cheaper kind of equipment, spending lower testing times. In fact, in Figure 3, The lowest stress CCS point corresponds to a tensile test duration for rupture of about 168 h with the UTS happening after about 65 h (~ 3 days). Of course, it seems quite inadequate to use an expensive constant crosshead speed machine for high temperature tests to generate data of longer durations in the creep region.

Both Steen[10] and Osgerby and Dyson[11] envisaged a correlation between strain rate and stress for tensile and creep testing in the same manner of this work, i.e., as expressed in rules 1 and 2 of the criterion presented in section 3. Both of them, however, did not mention the possibility of finding and equivalent for rupture time in the strain rate tests, as expressed in rule 3.

The present criterion was developed mainly on basis of experimental observation and if at all possible it should be supported by an appropriate physical theory. The work of Osgerby an Dyson[11] seems to provide the necessary mechanist equations for its confirmation. According to these authors, primary, secondary and tertiary creep behaviour can be described by the following equations:

$$\dot{\varepsilon} = \dot{\varepsilon}_o (\sigma/\sigma_o)^n (1-H)^n (1+S) (\exp \omega) \quad \text{.......................(1)}$$

with

$$dH/dt = (h\dot{\varepsilon}/\sigma)\{1 - [(1/H^* -1)/(1/H -1)]^n\} - H.{}^{d\sigma/dt}/\sigma \quad \text{............(1a)}$$

$$dS/dt = C\,\dot{\varepsilon} \quad \text{..(1b)}$$

$$d\omega/dt = k\,\dot{\varepsilon} \quad \text{.. (1c)}$$

$\dot{\varepsilon}_o$ is the initial creep rate of the material under the action of an applied stress σ_o ; n is the creep stress exponent ; **H** is a normalised internal stress, leading to primary creep, which has a saturation value **H*** and a hardening coefficient **h** ; **S** is a parameter describing tertiary creep due to dislocation softening and having an associated coefficient **C** ; ω is a parameter describing tertiary creep due to intergranular cavitation, having an associated coefficient **k** of magnitude **n**/3ε_f, where ε_f is the uniaxial strain to failure.

Figure 11a shows predicted stress-strain curves for a range of strain rates for a material with ε_f = 20%, according to Osgerby and Dyson:[11] the stress rises monotonically with increasing strain to a peak value, then decreases as the softening terms in the equation-set becomes dominant. The main influence of cavitation is to accelerate reduction of stress with strain after the peak stress, in low ductility materials. Figures 11b and 11c shows comparison of predictions for constant strain -rate and creep behaviour, in the form of the Norton and " Monkman-Grant" diagrams, respectively. There is coincidence in both behaviours in the first case. In the second case, however the time parameter in creep is not the rupture time t_r but the time to measure minimum creep rate which can be much lower than t_r. This could be a reason why the coincidence failed in the Monkman-Grant type plot of Figure 11c.

Figures 12a and 12b were taken by Osgerby and Dyson[11] for illustration of the success of their model in expressing both behaviours. Figures 12a shows the analysis of a creep curve from a material similar to Nimonic 101 tested in *constant load* at 800^{o}C and 300 MPa, to extract the model parameters and Figure 12b shows the predicted CSR (constant strain-rate) curve with experimental data superimposed for comparison. In both cases the fit between prediction and experiment is very good. According to Figure 12a the minimum creep rate $\dot{\varepsilon}_{min} \approx 1.4 \text{x} 10^{-4}$ h^{-1} and the time for its occurrence seems to be around 10h whilst the predicted rupture time happened at about ε_f = **n** / (3.**k**) = 3.6%, which gives $t_r \approx$ 68 h very close the experimental value of 66 h. Figure 12b shows that the strain at the predicted peak stress $\varepsilon_p \approx 0.005$ which means a time $t_p \approx$ 34 h to reach the peak, i.e. a value of t_p / t_r = ½ . A careful examination of Figure 12b shows however that the experimental peak stress attained a value of about 320 MPa, which would mean some degree of acceleration in the creep curve in Figure 12b had the test been carried out at this stress. For a material with **n**=5 (as assumed in the model) the estimated rupture time would decrease from 66 h to 47 h, which would give a value of t_p / t_r = 0.77. Considering the typical level of scatter that can be introduced in tensile and creep results by various kind of experimental factors[18-19] these times can be considered virtually identical specially when plotted in logarithmic scales like in Figures 3, 5, 9 and 10.

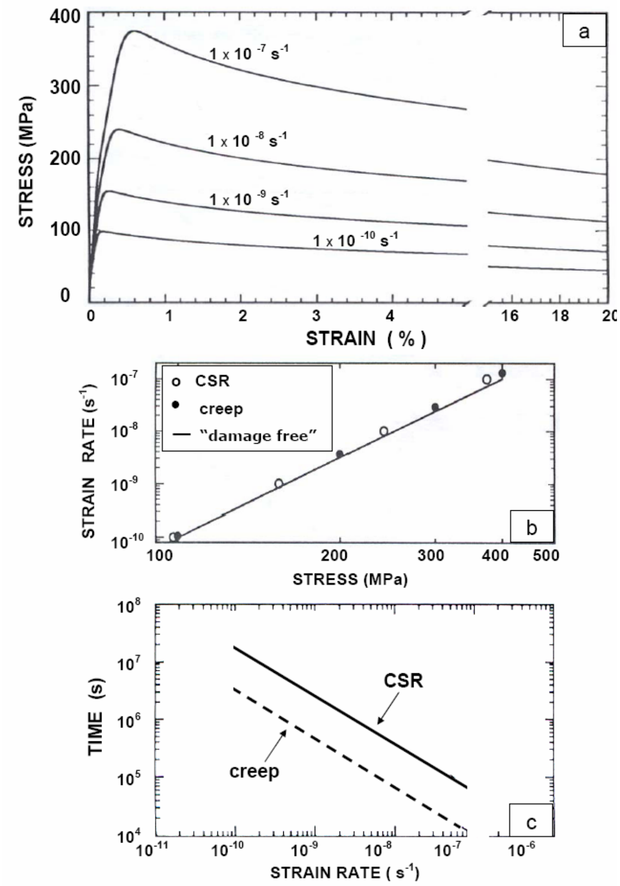

Figure 11. Predictions of the Osgerby and Dyson(11) with the following model parameters: $\dot{\boldsymbol{\varepsilon}}_{\mathbf{o}}$ = 1x10^{-7}s^{-1}, σ_o = 200 MPa, **n** = 5, **h** =1x10^5 MPa, H* = 0.5, C =100, $\boldsymbol{\varepsilon}_f$ = 20%; **a)** Stress-strain curves for material tested at different applied strain rates; **b)** Comparison of predictions for constant strain-rate and creep behaviour; **c)** Time to measure peak stress in constant strain-rate test or minimum creep rate in constant load tests as function of strain-rate.

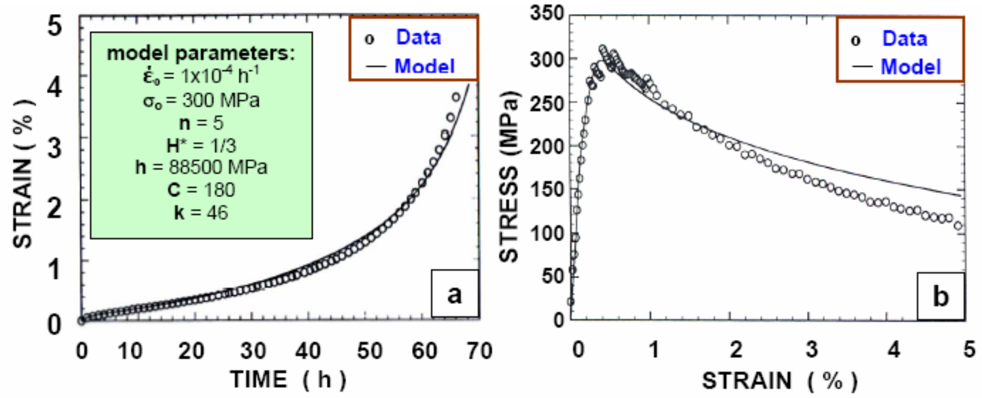

Figure 12. Example of analysis with the Osgerby and Dyson model(11): **a)** creep curve fitted to extract model parameters for the Equation set (1); **b)** Predicted stress/strain trajectory in constant strain-rate test at 1.4 x 10^{-4} h^{-1}.

6 CONCLUDING REMARKS

The criterion proposed in this work for converting hot tensile testing data to creep data presented results that were consistent and significant when confronted with real creep data obtained for AISI 310 Type stainless steel and 2.25Cr-1Mo steel, considering the main diagrams and relations suggested in the literature for analysis of creep behaviour. At least within the experimental conditions used in each case, the analysis indicated that CCS data can be converted to creep data and vice-versa according to the 3 rules established in this work. This procedure seems to have important implications and should be further explored, with more testing for its validation on other metallic materials.

The analysis of CCS data at 25°C, using the same criterion, indicated the possibility of occurrence of the creep phenomenon at room temperature, provided high stress levels are applied in the material, in the region where its strength is sensitive to strain rate. This should be also an interesting aspect to be explored in future.

A next topic for continuation of this research will be the analysis of the present sets of creep and CCS results on AISI Type 310 and 2.25Cr-1Mo according to the model of Osgerby and Dyson.[11] Another aim of the programme will be the generation of real CSR tensile tests and constant stress creep tests in 2.25Cr-1Mo to check the possible change in the parameters involved in the criterion in relation to those from CCS tensile tests and constant load tests.

Acknowledgements

The author acknowledges Dr. Tito Luiz da Silveira for supplying the tensile and creep specimens of the AISI Type 310 steel, Mr. Flavio A.Serra from Replan/Petrobrás for supplying the 2.25Cr-1Mo sheet sample, STM-Systems for Testing of Materials Ltd. for the preparation and testing of creep specimens of the 2.25Cr-1Mo steel and Mr. J.L.dos Santos for carrying out all the hot tensile tests. The author also acknowledges Mr. A.Contin Jr. and Dr.J.F.Reis Sobrinho for their help in the analysis of the data during their master and doctorate work, at DEMa/UFSCar.

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