ISSN 1516-392X

HOT TENSILE AND CREEP RUPTURE DATA EXTRAPOLATION ON 2.25Cr-1Mo STEEL USING THE CDM PENNY-KACHANOV METHODOLOGY[1]

José Francisco dos Reis Sobrinho [2]
Levi de Oliveira Bueno [3]

Abstract

Hot tensile and creep data were obtained for 2.25Cr-1Mo steel, ASTM A387 Gr.22CL2, at the temperatures of 500 - 550 - 600 - 650 - 700°C. Using the concept of equivalence between hot tensile data and creep data, both kind of results were analyzed according to the methodology based on Kachanov Continuum Damage Mechanics proposed by Penny, which suggests the possibility of using short time creep data obtained in laboratory for extrapolation to long operating times corresponding to tens of thousands hours. The hot tensile data (converted to creep) define in a better way the region where $\beta = 0$ and the creep data define the region where $\beta = 1$, according to the methodology. Extrapolation to 10,000 h and 100,000 h is performed and the results compared with data obtained by extrapolation using other procedures such as the Larson-Miller and Manson-Haferd methodologies, with the same data. ASTM Datasheet for 10,000 h and 100,000 h as well as data from other authors on 2.25Cr-1Mo steel are used for assessing the reliability of the results.

Keywords: 2.25Cr-1Mo steel; Hot tensile/creep data; CDM Penny methodology; Data extrapolation.

---

[1] *Technical contribution to 68th ABM International Congress, July, 30th to August 2nd, 2012, Belo Horizonte, MG, Brazil.*

[2] *Materials Engineering. DSc. Associate Professor of CEFET/Pi.*

[3] *Materials Engineering. PhD. Associate Professor of DEMa/UFSCar.*

1 INTRODUCTION

A simplified extrapolation procedure from shorter creep rupture data to longer times was proposed by Penny(1) based Continuum Damage Mechanics (CDM) concepts originally developed by Kachanov.(2) According to this method, the time to failure, t_f, is given by:

$$t_f = t_r - \bar{t} \qquad (1)$$

where

$$t_r = \frac{1}{Bk\,\sigma_0^k} \qquad (2a) \qquad \text{and} \qquad \bar{t} = \frac{1}{Bk\bar{\sigma}^k} \qquad (2b)$$

B and k are material constants obtained from curve fitting, σ_o is the initial stress and $\bar{\sigma}$ is the flow stress. The value of $\bar{\sigma}$ has a lower limit equal to the Yield Strength and an upper limit equal do the Ultimate Tensile Strength, and can be set equal to the stress level of a short-time creep rupture test for calculation and graphing purposes.

Figure 1 illustrates the stress-strain-time relationships for tensile deformation in general, involving tensile testing, creep testing and stress relaxation testing.(3)

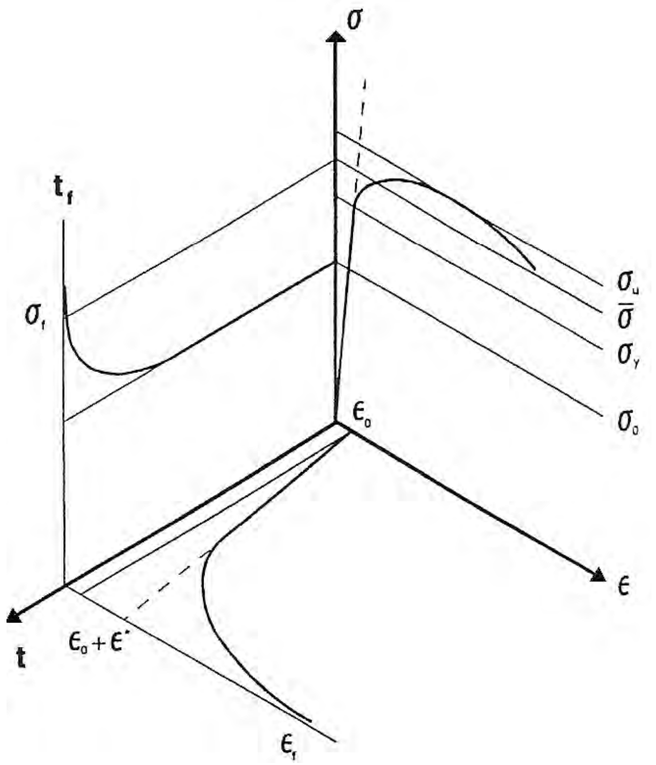


Figure 1 – Schematic stress-strain-time relationships in tension.(3)

Figure 2 shows schematically how the parameters t_f , t_r, β and k are defined on the modified Kachanov brittle rupture curve(3).

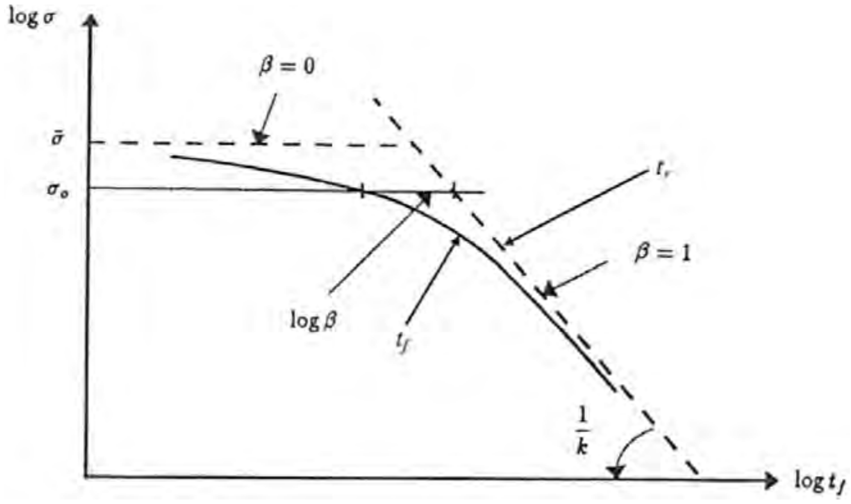


Figure 2 – The modified Kachanov brittle rupture curve.(3)

The performance of this method using curve fitting procedure has been discussed and several examples of extrapolation presented in literature.(1,4,5)

2 MATERIALS AND METHODS

The steel was supplied in plate form with 25.4 mm thickness, according to ASTM A 387, grade 22 class 2, 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 tests and creep tests were extracted from the rolling direction. A gauge length Lo = 25 mm and an initial diameter do = 6.25mm were used for all specimens.

The hot tensile tests were carried out in a servo-hydraulic 8802 model INSTRON machine, at 500°C, 550°C, 600°C, 650°C and 700°C, using the following constant crosshead speeds: 0,01 – 0,25 – 1,0 – 5,0 and 20 mm/min. In this way, 25 hot tensile tests were performed with a total variation of 3 orders of magnitude in strain rate, i.e. in the range from 6.7×10^{-6} to 1.3×10^{-2} s^{-1}.

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 a previous publication.(7,8) The elongation of the specimens was followed with creep extensometers having LVDT transducers. The readings from the transducers were collected by a Data Logger, 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 17 levels of applied stress, varying from 34.5 MPa to 414 MPa, so that 51 creep tests were produced with rupture times varying from 2 to about 1300 hours.

3 RESULTS AND DISCUSSION

Figure 3 shows the hot tensile data plotted together with the creep rupture data, using the criterion of equivalence between both kind of tests.(9,10) According to this criterion: the UTS, the nominal strain rate and the time to reach UTS in a hot

ISSN 1516-392X

tensile test corresponds respectivelly to the applied stress, the minimum creep rate and the rupture time in a creep test.

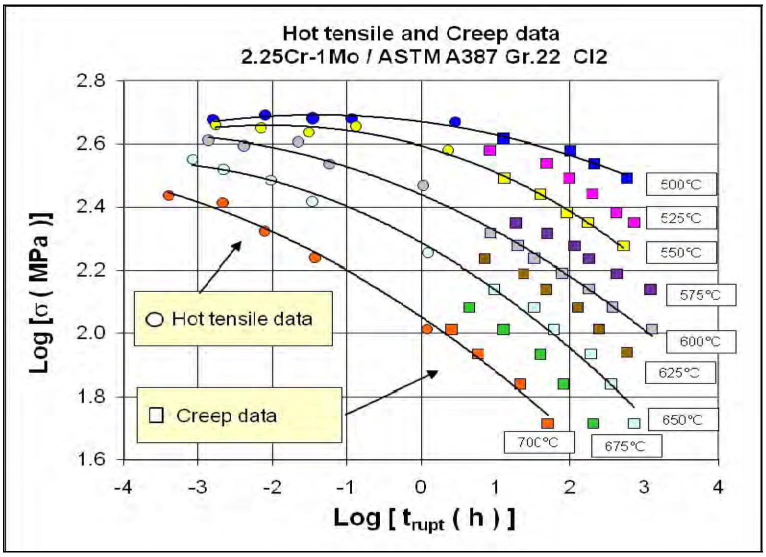
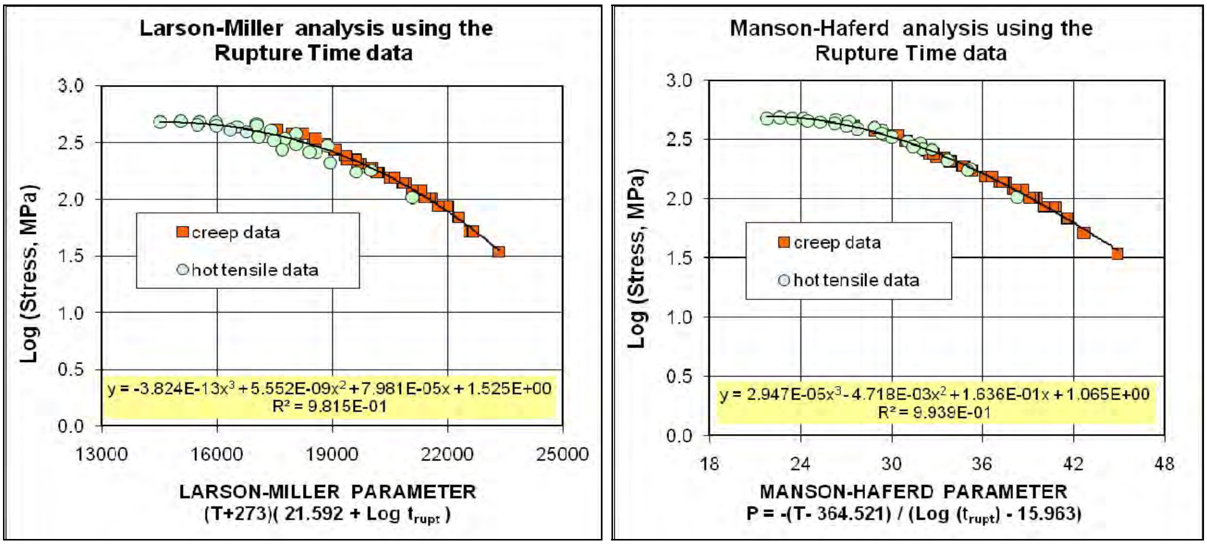


Figure 3 – Hot tensile data plotted with creep data, according to the equivalence criterion proposed for analysing both kind of results together.

The verification of validity of this methodology for various materials has been demonstrated in various publication.$^{(11-14)}$

Figure 4a and 4b show the data presented in Figure 3 subjected to parameterization analysis, according to two different procedures: the Larson-Miller and the Manson-Haferd methodologies, respectively.$^{(10)}$ Although the Larson-Miller analysis is more popular and widely applied for extrapolation in several situations, with the present data the best results were obtained with the analysis of Manson-Haferd, as evident from comparison between Figures 4a and 4b.$^{(15)}$



a) b)

Figure 4 – Hot tensile data plotted with creep data, according to the equivalence criterion proposed for analysing both kind of results together.

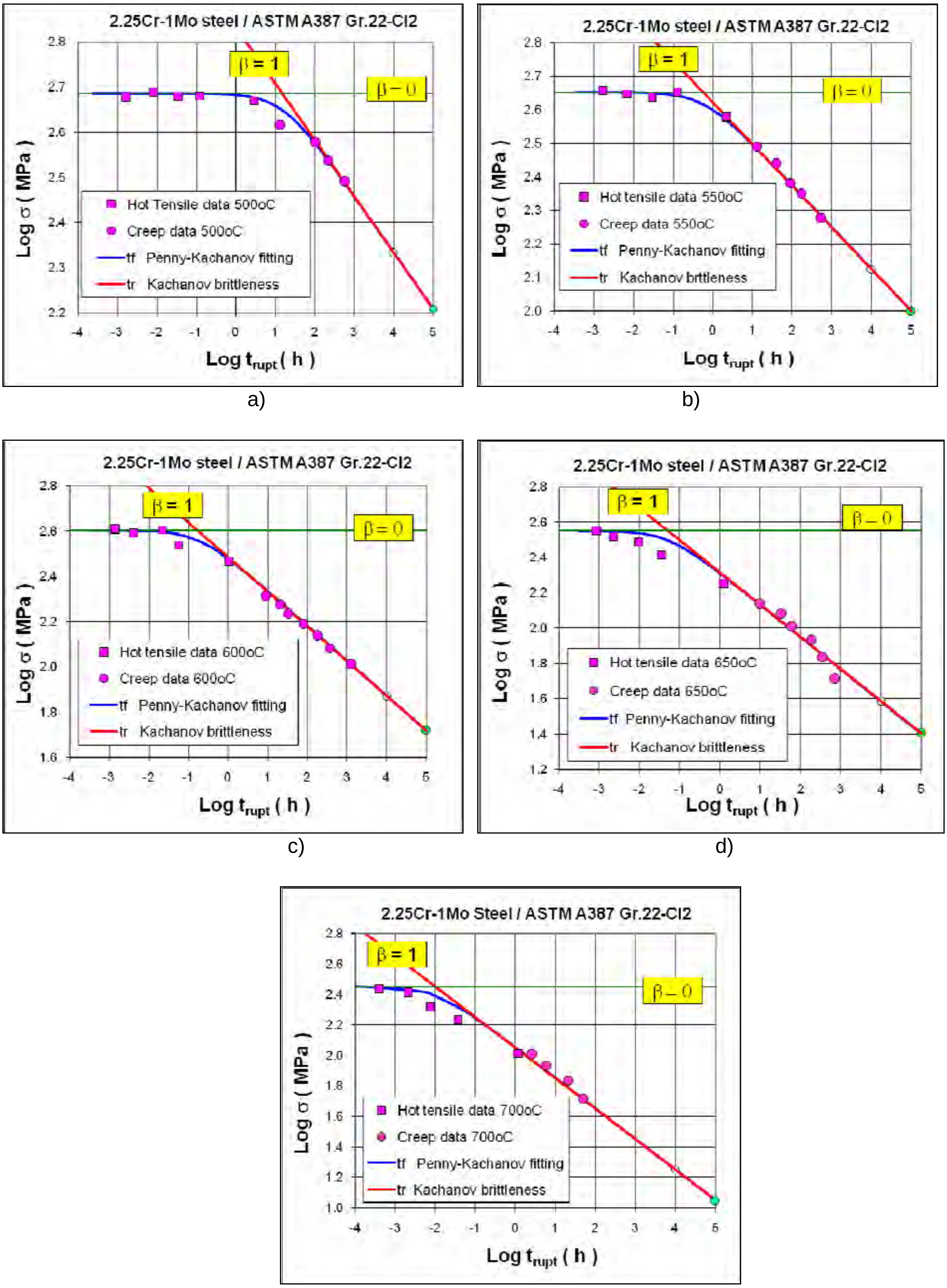
Figure 5a shows the hot tensile plotted together with creep data at 500°C on the diagram Log(σ) x Log(**t**$_{\mathbf{rupt}}$), with the curve $\boldsymbol{t_f}$ (in blue), determined by the Penny-Kachanov fitting, and the straight line corresponding to $\boldsymbol{t_r}$ Kachanov-brittleness obtained by extrapolation (in red). The rupture strengths predicted for 10,000 and 100,000 h are also indicated. The parameter $\mathbf{t_{rupt}}$ used to plot the experimental data corresponds here to the parameter $\boldsymbol{t_f}$ adopted by Penny$^{(1)}$ in his methodology.

Using a standard procedure of curve fitting, the following constants were determined: $k=$ 8, $\bar{\sigma}$ = 486.41 MPa, $\bar{t}$ = 15.000h, $Bk=$ 2.128x10^{-23} and $\bar{A}$ = 2.834. The stress levels for attaining 10,000h and 100,000h are, respectively, 215.7 MPa and 161.8 MPa. Several values of *k* were tried in the analysis, but finally it was chosen the value of *k* = 8, which was verified to minimize the sum of the squared error between the predicted and the observed ruptures times.

Figure 5b refers to the data obtained at 550^{o}C. In this case, the same procedure of analysis was applied, i.e. the value of *k* was best taken as $k=$ 8, and the following parameters determined: $\bar{\sigma}$ = 449.50 MPa, $\bar{t}$ = 0.600h, $Bk=$ 1.00x10^{-21} and $\bar{A}$ = 2.625. The stress levels for attaining 10,000h and 100,000h are, respectively, 133.4 MPa and 100.0 MPa at 550^{o}C.

Figure 5c refers to the data obtained at 600^{o}C. In this case, the value of k was best taken as $k=$ 6.5 and the parameters were: $\bar{\sigma}$ = 401.05 MPa, $\bar{t}$ = 0.180h e $Bk=$ 6.667x10^{-17} and $\bar{A}$ = 2.489. The stress levels for attaining 10,000h and 100,000 h are, respectively, 74.7 MPa and 52.4 MPa at 600^{o}C.

In the analysis of the data at 650^{o}C (Figure 5d) and 700 ^{o}C (Figure 5e) the value of k was best taken as $k=$5.5 and $k=$5.0, respectively, with the following set of parameters determined: $\bar{\sigma}$ = 375.26 MPa, $\bar{t}$ = 0.05h, $Bk=$ 1.818x10^{-13} and $\bar{A}$ = 2.316 for 650^{o}C and $\bar{\sigma}$ = 282.52 MPa, $\bar{t}$ = 0.01h, $Bk=$ 5.556x10^{-11} e $\bar{A}$ = 2.051 for 700^{o}C. The stress levels for 10,000 and 100,000 h are respectively: 38.8 MPa and 25.6 MPa at 650^{o}C, and 17.8 MPa and 11.2 MPa at 700^{o}C.



a)

b)

c)

d)

e)

Figure 5 – Hot tensile and creep data on 2.25Cr-1Mo steel analysed by the Penny procedure, at temperatures of : a) 500°C; b) 550°C; c) a600°C; d) 650°C; e) 700°C.

Table 1 – Variation of the parameters k, B, $\bar{\sigma}$, $\bar{t}$, $\sigma_{10,000h}$ and $\sigma_{100,000h}$ with temperature, according to the Penny-Kachanov analysis

T(°C)	k	B	$\bar{\sigma}$ (MPa)	$\bar{t}$ (h)	$\sigma_{10,000h}$	$\sigma_{100,000h}$
500	8.0	2.660E-24	486.41	15.000	215.7	161.8
550	8.0	1.250E-22	449.50	0.600	133.4	100.0
600	6.5	1.026E-17	401.05	0.180	74.7	52.4
650	5.5	3.306E-14	357.26	0.050	38.8	25.6
700	5.0	1.111E-11	282.52	0.010	17.8	11.2

Table 1 gives the complete set of values for the parameters k, **B**, $\bar{\sigma}$ and $\bar{t}$ and Figures 6a, 6b, 6c and 6d show, respectively, their variation with temperature.

Figure 6a and 6b indicate that the values of k and **B** decrease and increase linearly, respectively, with the increase in temperature and the legends in the figures present the regression coefficients determined for the data. According to Equation 2a and Figure 2, the value -1/k correspond to the slope of the Kachanov brittleness line, and it is easy to verify that the slopes of the curves in Figures 5a to 5e decrease as temperature increases, and therefore k decreases.

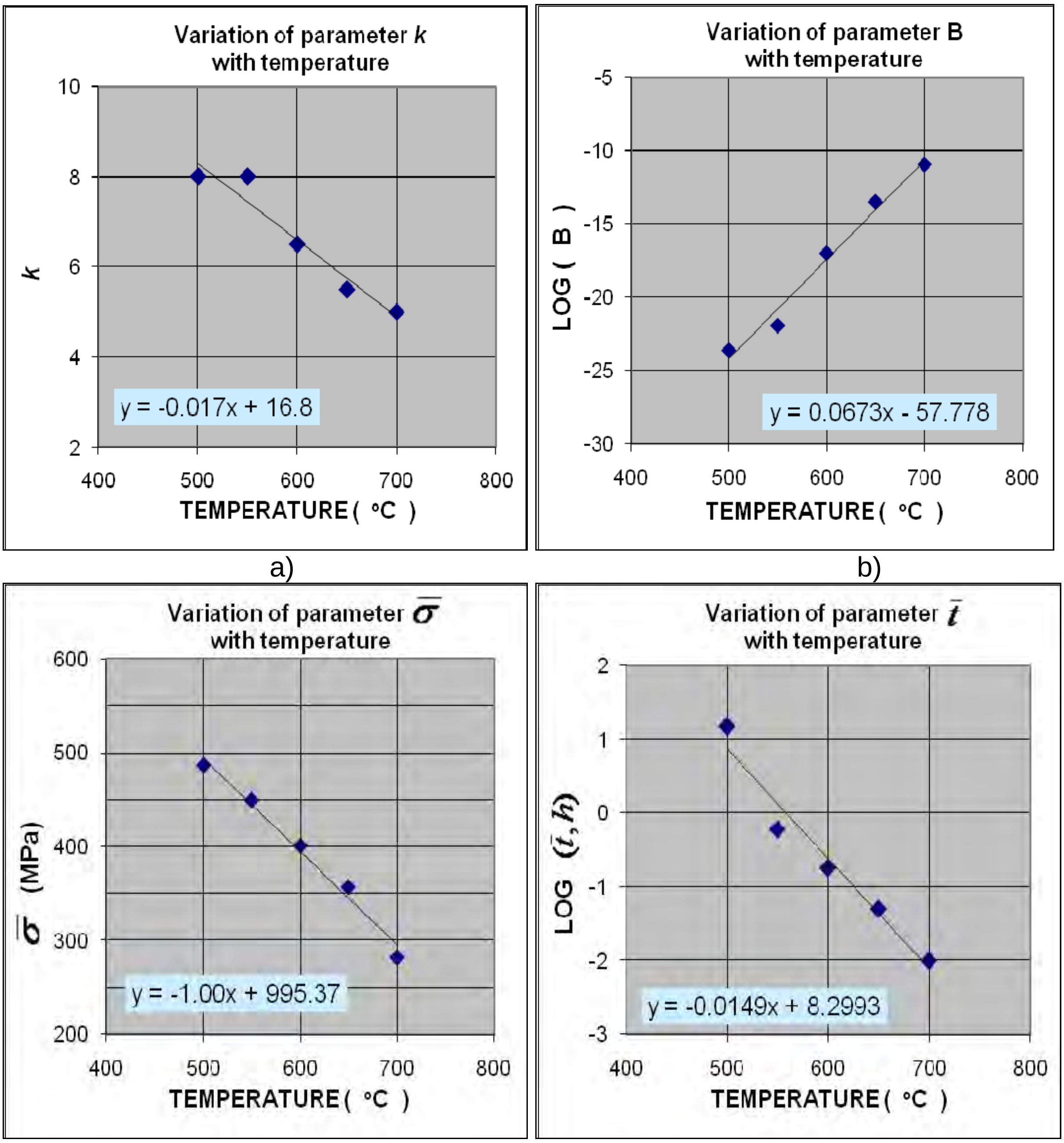
Figure 6c and 6d indicate that the parameters $\bar{\sigma}$ and $\bar{t}$ also decrease linearly with temperature. The values of $\bar{\sigma}$ are connected to the ultimate tensile stress of the material, and their reduction with temperature is a predictable behavior. The value of $\bar{t}$ corresponds to the intersection of the line t_r with the line of ultimate tensile stress $\bar{\sigma}$. The decrease of $\bar{t}$ with temperature is also a predictable behavior, since rupture times always decrease with increase in temperature at certain level of stress. The decrease of $\bar{t}$ with temperature is easily verified in Figures 5a to 5e.

It is important to emphazise the inclusion of the hot tensile data in the present analysis. These kind of data, expressed as creep data (using the criterion of equivalence mentioned previously (9)), proves to be very useful for defining the left side of the curve Log(σ) vs. (Log $\boldsymbol{t_f}$), in Figure 2, or of the curves Log(σ) vs. (Log $\mathbf{t_{rupt}}$) in Figures 5a to 5e. Thereby, the value of $\bar{\sigma}$ is better identified in the analysis. The values of $\bar{t}$ are also better characterized. A careful observation of Figures 5a to 5e, shows the evident decrease of $\bar{\sigma}$ and $\bar{t}$, as test temperature increases.

Figure 7a shows the variation of Creep Rupture Strength for 10,000h and for 100,000h for the 2.25Cr-1Mo steel under investigation, according to the analysis by the method of Penny-Kachanov(1,2). The present set of data (with 25 hot tensile results + 51 creep test results) were also analyzed by various traditional parameterization methodologies, like: Larson-Miller, Orr-Sherby-Dorn, Goldhoff-Sherby, Manson-Haferd and Manson-Succop(15). The results according to the methods of Larson-Miller and Manson-Haferd were presented in Figures 4a and 4b. With these two reference curves it was also possible to obtain data of $\boldsymbol{\sigma_{10,000h}}$ and $\boldsymbol{\sigma_{100,000h}}$. Data of these allowable stresses could also be obtained for 2.25Cr-1Mo steel in the normalized and tempered condition from the work of Viswanathan(16) and from the ASTM Special Report DS 6S1(17), that employed in both cases the Larson-Miller method in their analysis.

Figure 7b presents a comparison of the Creep Rupture Strength for 10,000h of the steel according to the Penny-Kachanov analysis with results of the same kind reported by the authors mentioned above. It can be observed that the Penny-

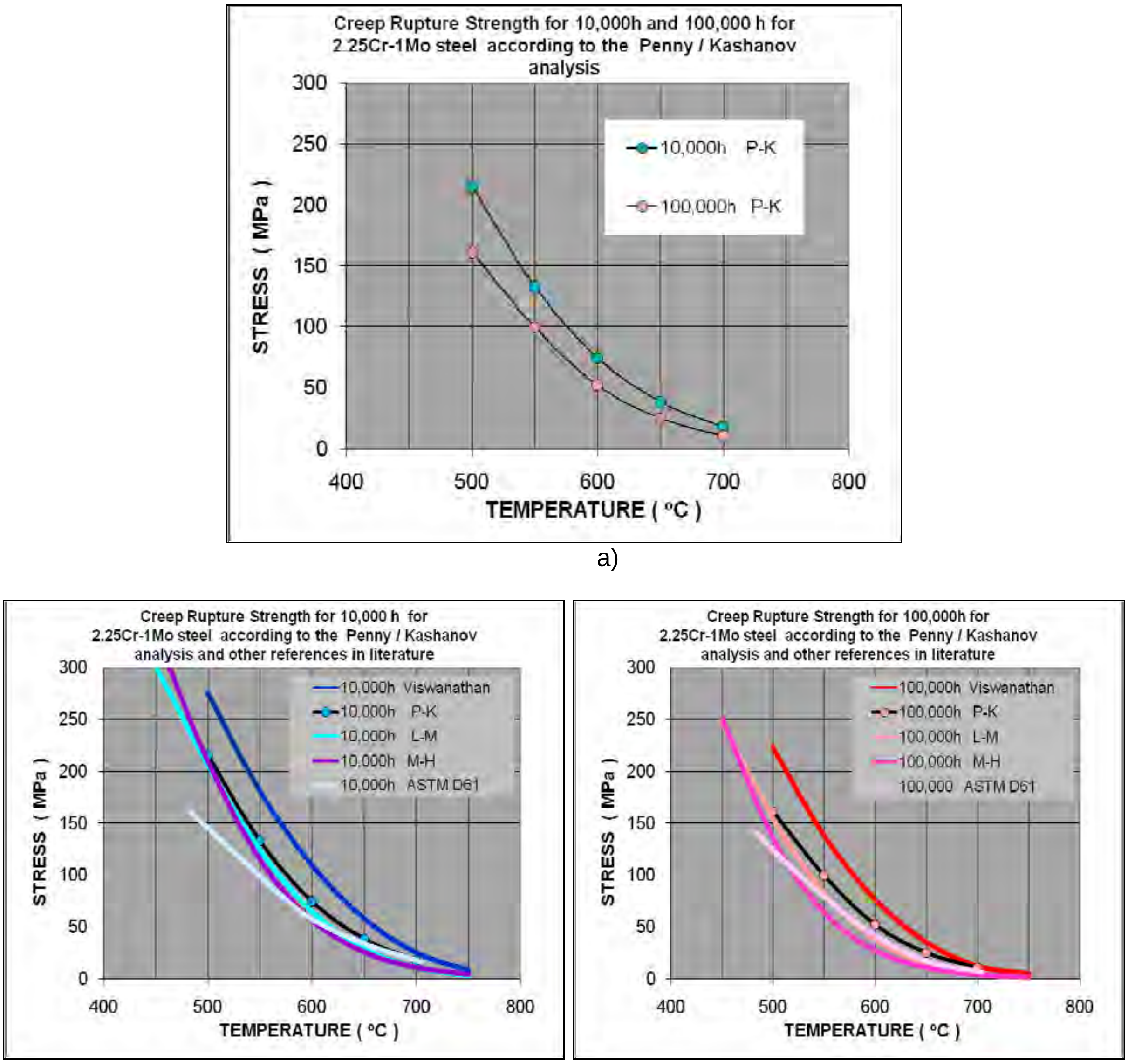
Kachanov curve is situated in between the Viswanathan’s curve (16), indicating higher creep rupture strength, and the ASTM curve, with lower creep rupture strength.



a) b)

c) d)

Figure 6 – Variation with temperature of the parameters: a) k ; b) ***B*** ; c) $\bar{\sigma}$; d) $\bar{t}$.



a)

b)

c)

Figure 7 – **a)** Creep rupture strength for 10,000h and 100,000 h estimated by the Penny-Kachanov method; **b)** Creep rupture strength for 10,000h compared with data from: Viswanathan,(16) ASTM D61,(17) Larson-Miller and Manson-Hafer extrapolations.(15)

The prediction made according to the Larson-Miller and Manson-Haferd methods is situated a little bellow the Penny-Kachanov curve.

In Figure 7b, the comparison refers to the Creep Rupture Strength for 100,000 h and approximately the same situation is verified: the Penny-Kachanov predictions is located again in between the four other curves.

It is important to point out that the creep rupture strength of the 2.25Cr-1Mo steel is highly dependent on the heat-treatment conditions employed in the manufacture of the material. Figure 8 shows data reported by Viswanathan(16) presenting Larson-Miller reference curves for this steel under four different heat-treatment states, with remarkable difference between them. Therefore, in the comparison illustrated in Figures 7b and 7c, involving the normalized and tempered version of the steel from various sources, and subjected to different procedures of analysis, it seems acceptable that the five curves present the observed differences between each other.

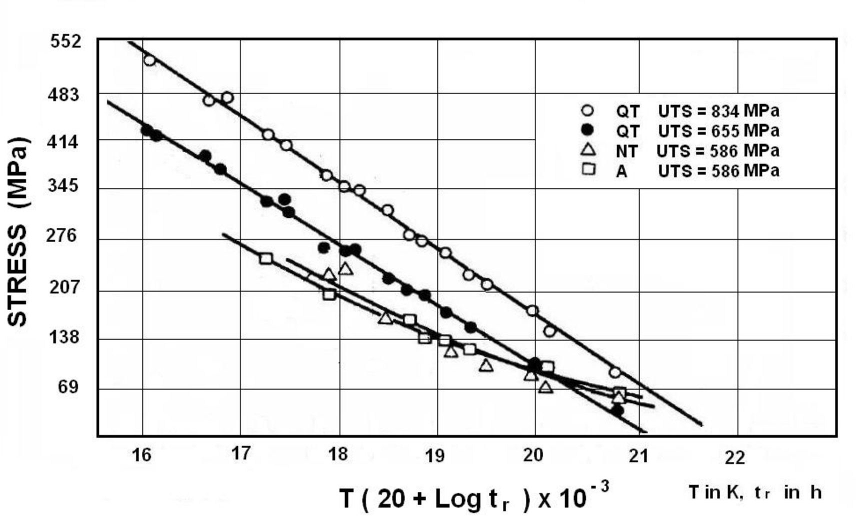


Figure 8 – Variation in Creep Rupture Strength of 2.25Cr-1Mo steel under different heat-treatment conditions, plotted using the Larson-Miller parameter. Q = quenched and tempered; NT = normalized and tempered; A = annealed; UTS = ultimate tensile stress. Obsv. Adapted from R.Viswanatan.(16)

It can be concluded that the Penny-Kachanov results obtained in this work are satisfactorily consistent and that the methodology seems viable to be employed with great advantage to generate data for long term operating times, from extrapolation of results of short duration produced in laboratory. However, its performance should be checked extensively with different metals and alloys for its effective validation.

4 CONCLUSIONS

- The methodology proposed by Penny(1), based on Kachanov work (2) was used to analyze a set of high temperature data from hot tensile and short duration creep tests, and it has been observed that the hot tensile data presents the great advantage or revealing better the region where β =0, and the creep data the region where β =1, according to the model.
- In the temperature range investigated, i.e. from 500^{o}C to 700^{o}C, the parameters k $\bar{\sigma}$ and LOG$\bar{t}$ where observed to decrease linearly with increase in temperature. On the other hand the parameter LOG **B** was observed to decrease linearly with increase in temperature.
- The Creep Rupture Strength of 10,000h and 100,000h were obtained by extrapolation from the Penny-Kachanov (1,2) methodology and the results are satisfactorily compatible with similar data from other sources in literature.
- Validation of the methodology should be tested with data as done in this work (hot tensile + creep) from different metals and alloys.

Acknowledgements

The authors acknowledge STM-Systems for Testing of Materials Ltd. for the preparation and testing of creep specimens, Mr. Flavio A. S. Serra from Replan/Petrobras for supplying the material, and CNPq / CAPES for a grant to J. F. Reis Sobrinho during his D.Sc. postgraduate program at PPG/CEM DEMa/UFSCar.

REFERENCES

1 PENNY,R.K. Practical methods for creep assessments: data extrapolation and crack propagation. In Proceedings of Failures 2002, Ed. R.K.Penny, EMAS, p.119-135 , 2002

2 KACHANOV, L.M. Rupture time under creep conditions. Izvestia Akademii Nauk SSST, Otdelenie Teknicheskich Nauk, N.8, p.26-31, 1958

3 PENNY, R.K.; MARIOTT, D.L. Design for Creep, 2. Ed., London, Chapman & Hall, 1995.

4 FURTADO, H.C.; LE MAY, I.; DE ALMEIDA, L.H.; PEACE, R. Extrapolation of shorter time creep rupture data using the Damage Mechanics approach of Penny. ASME/JSME Pressure Vessels and Piping Conference – Elevated Temperature Design and Analysis of Plastic Components. ASME, N. 472, p.11-17, 2004.

5 FURTADO, H.C.; LE MAY, I; PEACE, R. The application of Damage Mechanics concepts to creep data extrapolation and power plant life assessment. In Proceedings of ECCC Creep Conference, London, p.582-591, September 2005.

6 AMERICAN SOCIETY FOR TESTING AND MATERIALS, ASTM E 139-11, In: *Annual Book of ASTM Standards*, v. 03.01, p. 309-319, 2011.

7 BUENO, L.O. Máquinas-protótipos para ensaios de fluência em metais a altas temperaturas. Parte 1: Detalhes de construção e montagem do equipamento, In: *Anais do II ETUAN -Encontro de Tecnologia e Utilização dos Aços Nacionais*, p. 916-934, Rio de Janeiro (RJ), May 1987.

8 BUENO, L.O. ; PIGATIN, W.L, Máquinas-protótipos para ensaios de fluência em metais a altas temperaturas. Parte 2: Verificação de desempenho do equipamento na geração de dados de fluência, In: *Anais do II ETUAN-Encontro de Tecnologia e Utilização dos Aços Nacionais*, p. 935-948, Rio de Janeiro (RJ), May 1987.

9 BUENO, L.O. – Creep Behaviour of 2.25Cr-1Mo Steel - An equivalence between hot tensile and creep testing data. ECCC Creep Conference, 12-14 Setembro 2005, Londres – Proc. Creep & Fracture in High Temperature Components – Design and Life Assessment Issues – Editores: I.A.Shibli, S.R.Holdsworth, G.Merckling. DEStech Publ., USA., p.969-980, 2005.

10 REIS SOBRINHO, J.F. Tese de doutorado: Correlação entre os Comportamentos de Tração a Quente e Fluência do Aço 2,25Cr-1Mo na Faixa de Temperatura de 500°C a 700°C. PPG/CEM, UFSCar, 2004.

11 DIAS, C.R.F; BUENO, L.O. Correlação tração a quente e fluência para o cobre comercial puro. Parte 1: Relações entre tensão, taxa de deformação, tempo de ruptura e temperatura. In: *Anais 65º Congresso Anual da ABM,* p. 1246-55, Rio de Janeiro, 2010.

12 BUENO, L.O. Dados de Tração a Quente e Fluência no Alumínio Comercial Puro: Relações entre Tensão, Taxa de Deformação, Tempo de ruptura e Temperatura. Anais do Seminário de Metais Não Ferrosos ABM 2011, São Paulo, in CD ROM.

13 BUENO, L.O. Tração a Quente e Fluência no Latão Comercial. Parte 1: Relações entre Tensão, Taxa de Deformação, Tempo de Ruptura e Temperatura. Anais do Seminário de Metais Não Ferrosos ABM 2011, São Paulo, in CD ROM.

14 BUENO, L.O. and REIS SOBRINHO, J.F., Correlation Between Creep and Hot Tensile Behavior 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, Revista Materia, v. 10, n. 3, pp. 463 – 471, 2012.

15 REIS SOBRINHO, J.F; BUENO, L.O.Correlation Between Creep and Hot Tensile Behaviour for 2.25Cr-1Mo Steel from 500°C to 700°C. Part 2: An Assessment According to usual Relations Involving Stress, Temperature, Strain Rate and Rupture Time. Revista Matéria, v. 10, n. 3, pp. 463 – 471, 2005.

16 VISWANATHAN, R. Damage Mechanisms and Life Assessment of High-Temperature Components, ASM International, Palo Alto, CA, USA, 1993.

17 AMERICAN SOCIETY FOR TESTING AND MATERIALS, ASTM. Supplemental Report of the Elevated-Temperature Properties or Chromium-Molybdenum Steels. Data Series Publication DS 6S1, Ed. and W.F.Simmons, J.A.VanEcho and H.C.Cross, Philadelphia, USA, 1966.