

CREEP BEHAVIOR ON TYPE 310 STAINLESS STEEL. PART 3: CORRELATIONS OF THE STRESS EXPONENT AND ACTIVATION ENERGY VALUES WITH THE DORN CONSTANT¹

*José Luiz Campanelli²
Levi de Oliveira Bueno³*

Abstract

Creep strain rate behavior was studied by small stress increments/decrements performed at six strain levels from 2 to 25% involving primary, secondary and tertiary creep stages, during constant stress creep tests at six stress levels from 90 to 250 MPa, at 700°C, on Type 310 stainless steel, as continuation of the works reported in Part 1 and Part 2. Relationship between the stress exponents n and the Dorn constant A for power law creep at the different strain levels was verified in the form: $\text{Log } A \approx 2.5(n - 2.9)$, as suggested by Stoker and Ashby and other authors in the past, from the analysis of secondary creep data with different materials. In the same way, with a set of small temperature change experiments, above and below the test temperature, in the same strain levels, for three values of applied stress: 120, 180 and 240 MPa, a linear correlation could be established between the constant A and values of the apparent creep activation energy Q_c in the form $\text{Ln } A = 0,136(Q_c - 269)$. The set of values: $n=3$, $A=1$ and $Q_c=270$ kJ/mol (the activation energy for lattice self-diffusion of Iron in austenite) seems to represent a natural creep condition for the material, when the effect of internal stresses is taken into account during this deformation process, regardless the creep stage (primary, secondary or tertiary). The results presented in Parts 1 and 2 of this work are considered and a general discussion implemented involving internal stress and the parameters n , A , and Q_c .

Keywords : Type 310 stainless steel, creep behavior, stress/temperature changes, stress exponent, Dorn constant, creep activation energy.

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² *Materials Engineering. MSc. PPG/CEM – UFSCar. São Carlos, SP, Brazil.*

³ *Mechanical Engineering. PhD. Associate Professor of DEMa/UFSCar. São Carlos, SP, Brazil.*

1 INTRODUCTION

It has been well established nowadays that at high temperatures (above $T_m/2$, T_m = melting point of the material, in absolute temperature) creep behavior at *steady state* of a great number of metallic and non-metallic materials is described by the Dorn equation:⁽¹⁻³⁾

$$\dot{\epsilon}_s = A. [(DGb) / (kT)]. (\sigma/G)^n \quad (1)$$

where **D** is the appropriate coefficient of diffusion, **G** the shear modulus, **b** Burgers vector, **k** Boltzmann constant, **T** absolute temperature, σ the applied stress, **n** a dimensionless constant of the material known as stress exponent or Norton exponent, and **A** also a dimensionless parameter of the material known as Dorn constant.

Exactly four decades ago, Stoker and Ashby⁽⁴⁾ noticed that a strong correlation exists between the dimensionless parameters of the material **A** and **n**. An investigation of creep data over 50 different materials revealed that the values of Log **A** versus **n** is remarkably linear, over 16 orders of magnitude for the values of **A** with **n** values varying from 3 to 7. The relation found for these constants was:

$$\text{Log}A = 3.4 n - 10,5 \approx 3,4 (n - 3.1) \quad (2)$$

Some time later, the approximation of Stoker and Ashby⁽⁴⁾ was developed by Brown and Ashby⁽⁵⁾ who showed that the two coefficients in Equation 2 exhibit values slightly different depending on the class of material (metals and alloys CCC, FCC and HCP, oxides and alkali halides). By the combination of the linear relation between Log**A** and **n** with Equation 1 for different materials, general equations for creep (named "Archetypal Creep Equations") were obtained for each class of material with common characteristics among them. The **A** - **n** relationship and the Archetypal Creep Equation proposed by Brown and Ashby for FCC and HCP metals and alloys were:

$$\text{Log}A = 2.94(n - 2.95) \quad (3a)$$

$$\dot{\epsilon}_s = 2.1 \times 10^{-9} . [(DGb) / (kT)]. (\sigma / \sigma_o)^n \quad (3b)$$

where $\sigma_o = G / 870$

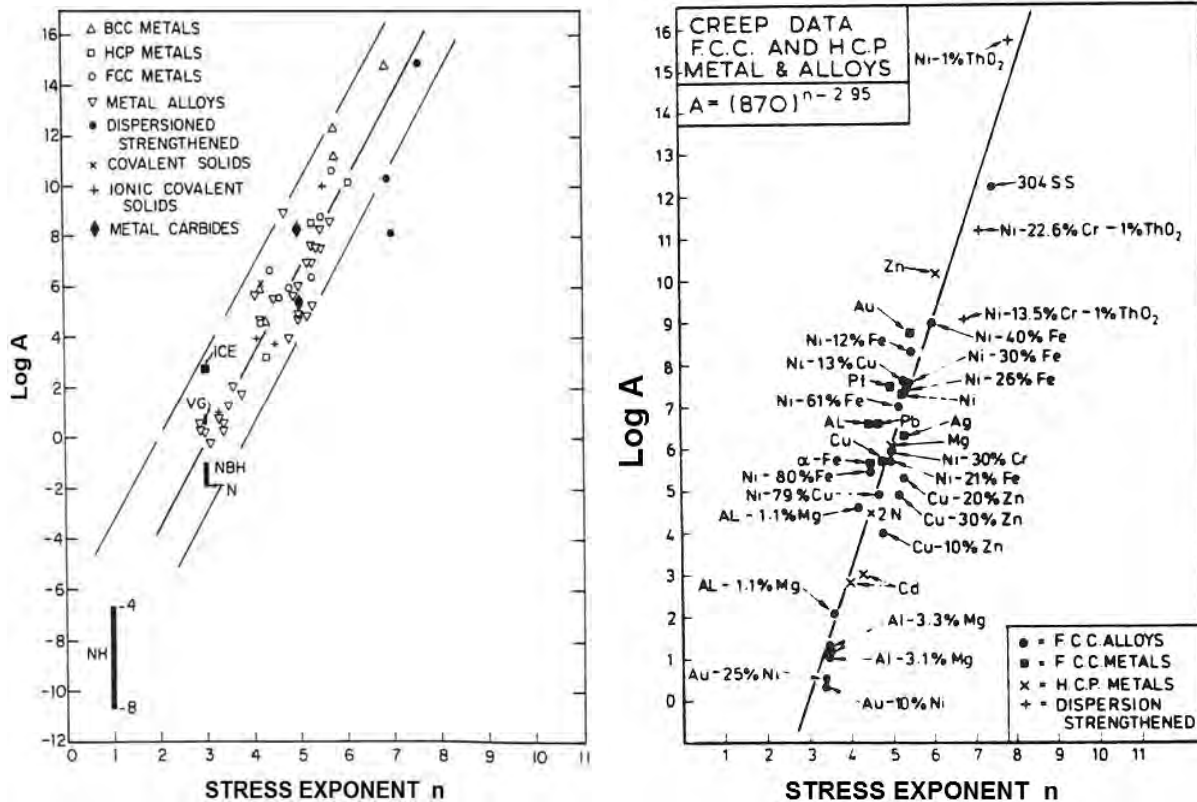


Figure 1 – Correlation between **A** and **n** for: **a)** various classes of crystalline solids, according to Stoker and Ashby⁽⁴⁾; **b)** Metals and alloys FCC and HCP, according to Brown and Ashby.⁽⁵⁾

However, the results of Brown and Ashby⁽⁵⁾ were later criticized by Walser and Sherby⁽⁷⁾ who pointed out these equations did not contain in their formulation more specific micro-structural factors, which are known to have great effect in creep strain rate^(1,8).

The correlation between **A** and **n** is important for various reasons. First, because **A** and **n** are unknown parameters of the material and if the correlation between them is determined, the number of terms in the Dorn equation could be reduced from two to one. Second, because the correlation was considered by various researchers as a fundamental hypothesis for the concept that the value **n** = 3 is the “natural exponent” of stress for creep process.

A physical explanation for the correlation between **A** and **n** was proposed by Derby and Ashby.⁽⁸⁾ They showed that the incorporation of the internal and threshold stress in a “natural” potential law of creep with stress exponent 3 makes possible the determination of a relation between **A** and **n** in the form of Equation 2. However, this model is not entirely satisfactory when it makes use of the concept of “threshold stress” since this behavior was verified for only a limited number of materials.

The objective of the present study was to verify the behavior of the **A**, **n** and **Q_c** parameters of the Dorn Equation, for stainless steel AISI 310, at 700°C, when creep deformation rates are measured after small variations in stress and temperature at various strain levels during creep tests, involving the primary, secondary and tertiary stages. The reason for doing the investigation in various strain levels during creep, and not exclusively in the secondary creep stage, is associated to the query posed by various authors on the existence of a real steady-state stage during creep.⁽³⁾

2 MATERIALS AND METHODS

As proceeded in Part 1⁽⁹⁾ of the work, a segment of bar with ½" diameter of AISI 310 stainless steel was also used. Details of state of the material, chemical composition, grain size, specimen preparation and creep test techniques, etc were presented in that article.⁽⁹⁾ In the same way, all creep tests were performed under *constant stress* condition.

2.1 Tests with Small Stress Variations

A first set of creep tests was carried out at 700°C, with 6 levels of applied stress, namely : 90 – 120 – 150 – 180 – 210 – 250 MPa. Small stress variations were applied in each test, in six different levels of accumulated creep strain, namely: 2 – 5 – 9 – 14 – 20 – 25%. The experimental procedure with these experiments was as follows: after having established the first level of deformation (2%), applied the stress was gradually decreased by about -10 MPa, in three steps (totalizing -30 MPa), taking care to wait, after each unloading operation, the definition of a new creep rate in the reduced stress levels. After that, the applied stress was gradually increased by +10 MPa, in six steps (reaching +30 MPa above the original stress level), and finally the stress was decrease again by -10 MPa, in three steps, reaching the initial stress level of the test. It is important to mention that after each of these stress variations, care was taken also not to leave the specimen creep exaggeratedly: as soon as a new constant creep rate could be identified, another stress variation was performed. In general, after each stress variation the increment of strain was of the order of 0.05%. After the first sequence of stress variation of this kind, the specimen was left to creep at the original applied stress in the test, until reaching the next strain levels (9 – 14 – 20 – 25 %) to be subjected to another stress variation sequence, as shown in Figure 2. With this procedure a record of 13 pairs of values of creep strain rate vs. stress was obtained for each strain level of a certain creep curve.

2.2. Tests with Small Stress Temperature Variations

A second set of creep tests was carried out at 700°C, with 3 levels of applied stress, namely: 120 – 180 – 240 MPa. As done in the previous case, five levels of creep strain were selected to perform the variations, in this case : 2 – 5 – 9 – 14 – 20 %. In each tests, when these predetermined strain levels were attained, the original temperature (700°C) was decreased by -10°C, in two steps, until the level of 680°C, being subsequently increase by +10°C, in four steps, until the level of 720°C. Finally, the temperature was decreased again by -10°C, in two steps, to reach the original test temperature of 700°C. It is important to point out that, after each temperature variation care was taken to wait for the definition of a new constant creep rate. After the first sequence of temperature variation of this kind, the specimen was left to creep at the original temperature of the test, until reaching the next strain levels (9 – 14 – 20 – 25 %) to be subjected to another sequence of temperature variation, as show in Figure 2. With this procedure a record of 9 pairs of values of creep strain rate vs. temperature was obtained for each strain level of a certain creep curve. In general, the total deformation accumulated after each session of temperature variation was relatively higher than those obtained in the case of stress variation. For the higher stress level, 240 MPa, for instance, at the higher temperature levels the strain increment was of the order of 0.2%. This happened because it always

necessary to wait for about 10 minutes for temperature stabilization when variations of 10°C were performed, so as to make an adequate record the new creep rate. Therefore, the time spent in this kind of experiments was also relatively longer. This was the reason for selecting a lower number of steps for temperature variation, in relation to the situation described in the previous section.

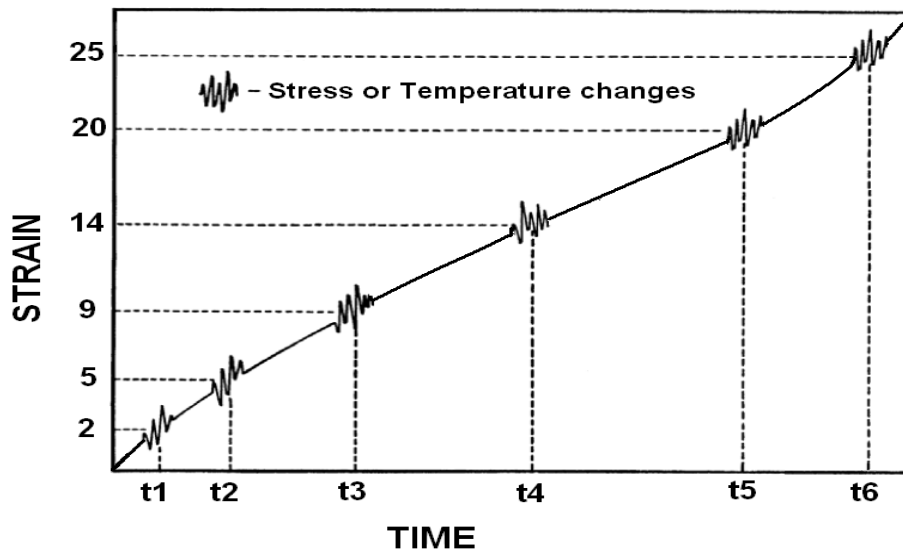


Figure 2 – Schematic diagram of a test with small stress or temperature variation in different creep strain levels. In the case of temperature variation, the strain level of 25% was not explored.

It is important to emphasize that the stress and temperature alterations were carried out in creep levels comprising the three stages: primary, secondary and tertiary. Care was taken though, not to have any evidence of drastic acceleration of creep strain rate which is characteristic of the last portion of tertiary stage leading to rupture of the specimen. It was always possible to verify that the accumulated deformation after the various sequences of changes in each specimen consisted predominantly of uniform plastic deformation, i.e. deformation without the presence of the effect of necking. This observation indicated reliability on the assumption of the constant stress condition conferred by the Andrade-Chalmers profile during the tests.

3 RESULTS AND DISCUSSION

3.1 Tests with Small Stress Variations

Figure 3 shows examples of creep curves of AISI 310 steel at 700°C, by comparing continuous tests until rupture with tests interrupted for stress variation at different strain levels. It is noticed that the curves from the tests with stress variation present similar behavior with the continuous curves. This seems to indicate that the procedure of small variation in stress used in this work have not significantly altered the creep process in the main level of test without any stress variation.

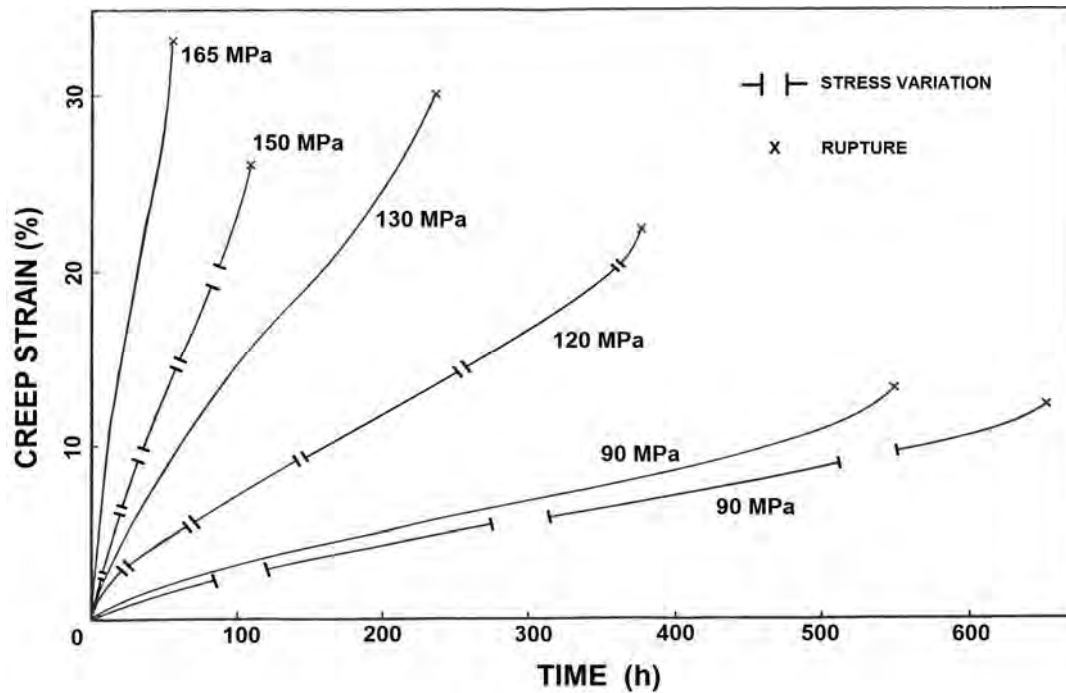


Figure 3 – Examples of creep curves of AISI 310 at 700°C. The interrupted curves correspond to the tests with stress variations carried out in the present work. The continuous curves correspond to tests without stress variation from the work of Contin Junior and Bueno.⁽⁹⁾

Figure 4 presents an example of data of strain rate versus stress obtained in the test with applied stress of 120 MPa, at the level of 5% strain. A total of 26 graphs of this kind were obtained for the various applied stresses and creep strain levels. It can be observed that the set of data can be represented by a single straight line, involving a linear regression of 13 points. In this way, it was possible to obtain the value of the stress exponent n (slope of the line), as well as of the constant $\text{Log } A'$ (intercept of the line with the Y-axis). Therefore, 26 pairs of data of $\text{Log } A'$ versus n were gathered for the different levels of creep strain and applied stress in the tests.

Figure 5a illustrates the behavior of the stress exponent n at the various strain and stress levels selected for investigation. It observed that for 180, 210 and 250 MPa the stress exponent increases with creep strain level. On the other hand, for 120 and 150 MPa, the n exponent exhibits a minimum value at 5% strain and a maximum value for 14% strain. For 90 MPa the data shows similar behavior to the data of 120 and 150 MPa, until 9% strain; the other strain levels could not be explored because the specimen fractured before 14% strain. It is interesting to mention that for the tests at 180, 210 and 250 MPa it was not possible to obtain with confidence the data for 2% strain, since during the load application in these tests the instantaneous strain was always greater than 2%.

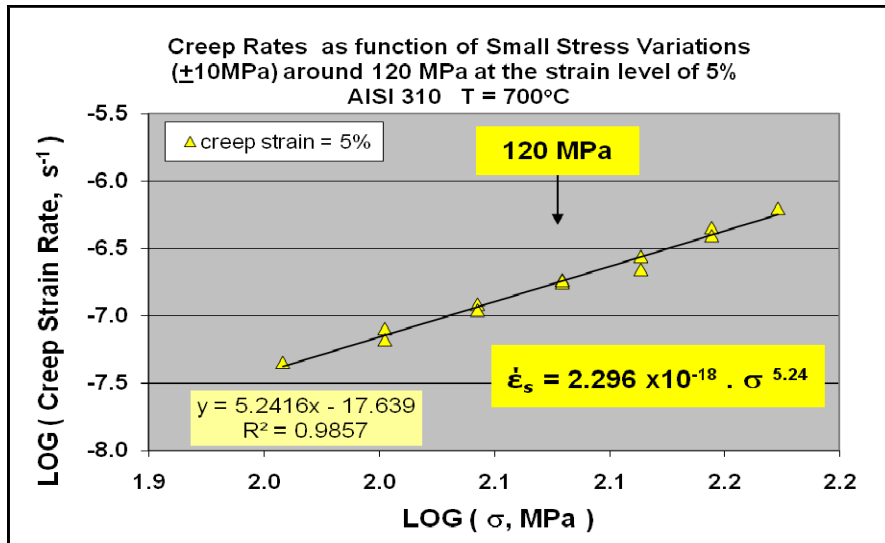


Figure 4 – Example of Creep Strain Rate data as function of Stress after small changes in stress (± 10 MPa) around 120 MPa at the strain level of 5% at 700°C.

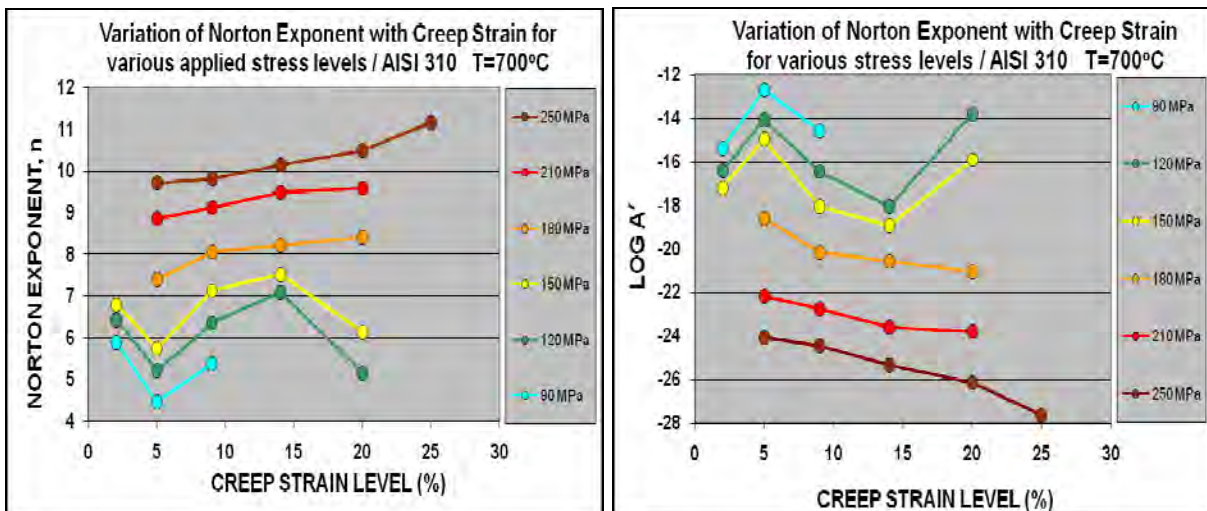


Figure 5 – **a)** Variation of Norton Exponents (n) with Creep Strain; **b)** Variation of LogA' with Creep Strain. Data from small stress changes during creep at 700°C in various applied stress levels.

Figure 5b shows how the parameter LogA' varies with creep strain level in the various tests. For the tests at 180, 210 and 250 MPa, the values of LogA' decrease with the increase in creep strain. For the tests at 90, 120 and 150 MPa the values of LogA' present a maximum value at 5% strain and a minimum value for 14% strain.

Figure 6a contains all the data of LogA' versus n . It is clearly noticed that all the set of data can be very well adjusted by a single straight line. Taking a linear regression through the 26 points, the following equation was obtained:

$$\text{LogA}' = -2.2802n - 5.5187 = -2.2795(n + 2.4207) \quad (4)$$

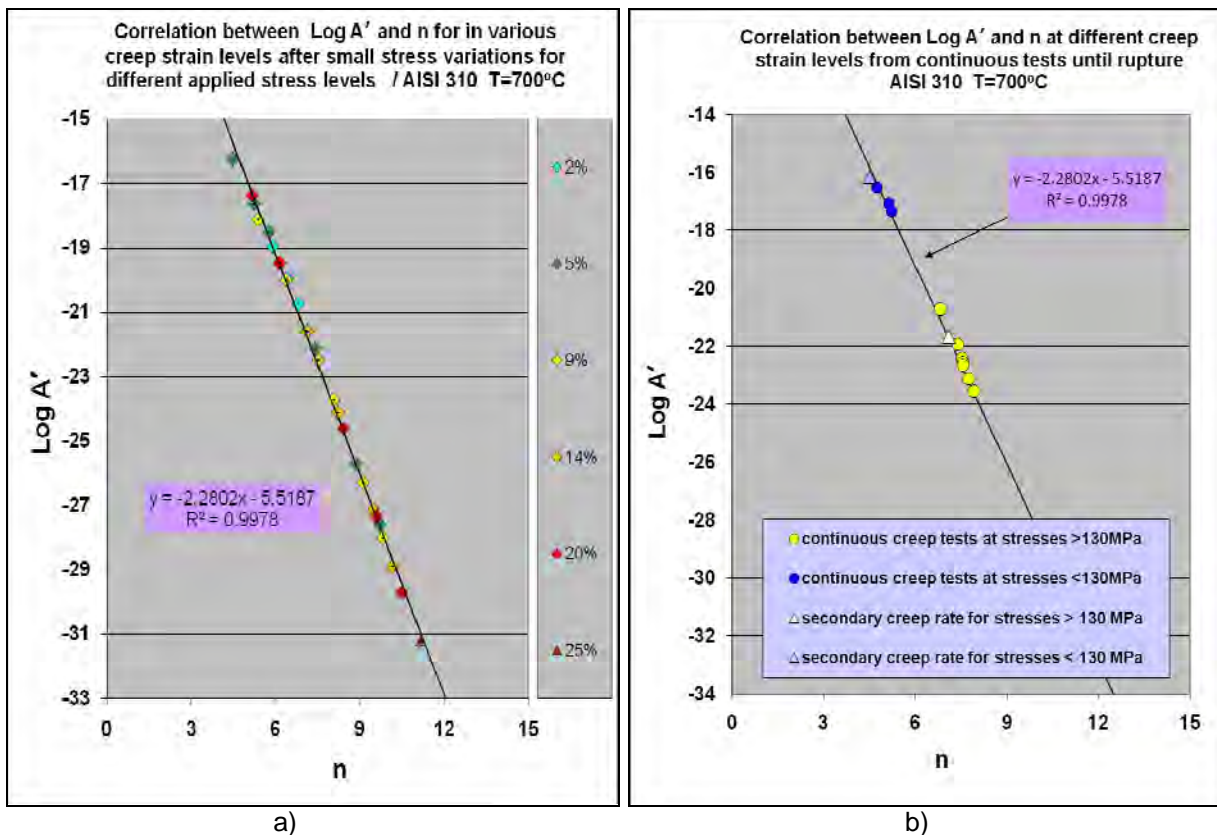


Figure 6a – a) Correlation between $\text{Log } A'$ and n at various strain levels after small stress variations; b) Correlation between $\text{Log } A'$ and n in different creep strain levels using the curves from continuous creep tests until rupture at 700°C (round symbols). Data of secondary creep for $\sigma < 130 \text{ MPa}$ and $\sigma > 130 \text{ MPa}$ (triangle symbols) are also superimposed. Straight line obtained with data from small stress variations during creep (represented in Figures 6a and 6b) is also shown, for comparison.

In Figure 6b the creep rates from continuous creep tests carried out until rupture are represented. In this figure the straight line from Figure 6a is reproduced for reference. The results of Contin Junior and Bueno⁽⁹⁾ have indicated that the secondary creep rates for uninterrupted creep tests from 70 to 375 MPa, at 700°C , present two potential relations with: $n=4.5$ and $\text{Log } A'=-16.162$ for stresses lower than 130 MPa, and $n=7.1$ and $\text{Log } A'=-21.661$ for stresses higher than 130 MPa. These two pair of values are plotted in Figure 6b, represented by the triangle symbols, and their proximity to the straight line imported from Figure 6a is remarkable. An analysis was made using all the continuous creep curves reported by Contin Jr. and Bueno⁽⁹⁾, so as to obtain values of creep strain rates in different strain levels, namely: 2 – 5 – 9 – 14 – 20 – 25 and even 30%. Eleven tests of this kind were carried at the following stresses: 90 – 130 – 140 – 165 – 180 – 210 – 250 – 300 – 344 – 375 MPa. At each strain level, creep strain rate readings were taken from the continuous curves, whenever possible, and the regressions parameter calculated to obtain the values of $\text{Log } A'$ and n . Two groups of strain rate readings were produced: one for stresses bellow 130 MPa and another for stresses higher than 130 MPa. These data are also plotted in Figura 6b and, in the same way the agreement with the other data is outstanding.

As shown in Figure 4, the potential creep law was always verified for the 26 sets of data with small stress variation, i.e. the results indicated that Norton relation is valid:

$$\dot{\epsilon}_s = A' \cdot \sigma^n \quad (5)$$

Comparing the Norton relation (Equation 4) with the Dorn Equation (Equation 1), it is possible to express the parameter A' as function of the Dorn constant A , i.e.:

$$A' = (DGb/kT) \cdot (A / G^n) \quad (6)$$

Using the reference work of Frost and Ashby⁽²⁾, for stainless steels of series 300, the values of the following parameters were taken for Type 310 steel in the calculation of Equation 6:

$$D=3.436 \times 10^{-20} \text{ m}^2/\text{s}; \quad G=55400 \text{ MPa}; \quad b=2.58 \times 10^{-10} \text{ m}; \quad k = 1.381 \times 10^{-23} \text{ J/K}; \quad T= 973 \text{ K}$$

Therefore,

$$A' = 3.6549 \times 10^{-5} A / (55400)^n \quad (7)$$

Finally, comparing Equation 7 with Equation 4, the following relation is derived between A and n :

$$\text{Log}A = 2.46 (n - 2.87) \quad (8)$$

The data of $\text{Log}A$ versus n is plotted in Figure 7 and fully confirms Equation 8. This equation exhibits great similarity with Equation 3a proposed by Brown and Ashby⁽⁵⁾ for FCC metals and alloys and the data in Figure 7 extends over 17 orders of magnitude for the values of A with n values varying from about 4.5 to 10.5. Moreover, the value 2.87 is very close to the value $n = 3$ proposed by Derby and Ashby⁽⁵⁾ as a “natural” exponent for the creep processes in solids in general.

Therefore, with Figure 7, the present study demonstrates the existence of a remarkable linear relation between the Dorn constant A and the Norton exponent n in AISI 310 steel, in creep tests at the temperature level of 700°C, subjected to small stress variation in a number of creep strain levels including primary, secondary and tertiary stages.

3.2 Tests with Small Temperature Variations

Figure 8 shows a comparison of a creep curve after temperature variation and curve after stress variation. It is noticed that both curves present similar behavior, and it is viable to suppose that the sequence of small temperature variation applied in this kind of test also have not altered significantly the creep process in the material, as already commented in relation to Figure 3.

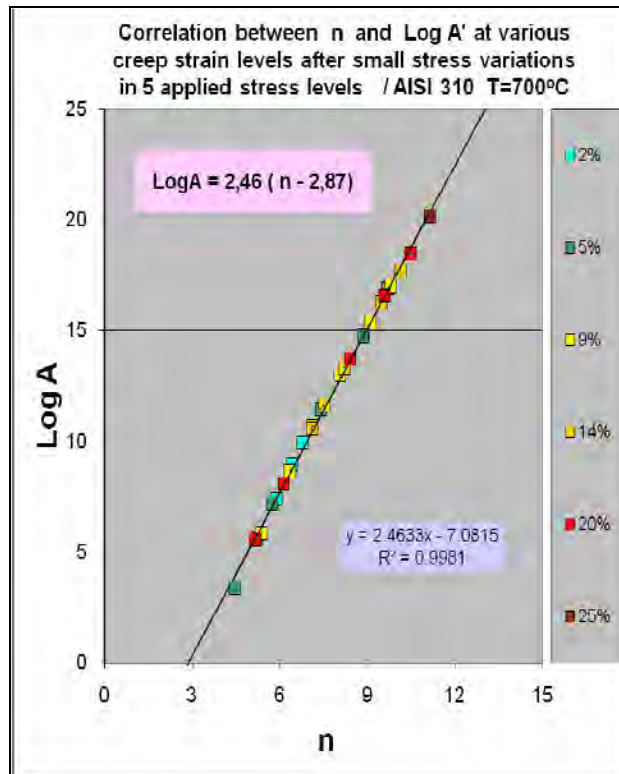


Figure 7 – Correlation between LogA and n at various strain levels after small stress variations in different stress levels.

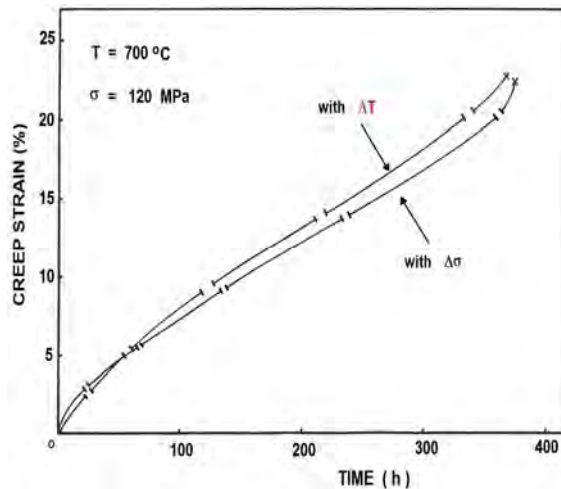


Figure 8 – Comparison of a creep curve with small temperature variation and a curve with small stress variation, for a test temperature of 700°C and applied stress of 120 MPa.

Figure 9a presents three examples of data of variation of strain rate with the inverse of temperature at the strain level of 9%, for the tests at 120, 180 and 240 MPa. The data can be very well represented by straight lines, so that an Arrhenius type equation can be used to express the results:

$$\dot{\epsilon}_s = B \cdot \exp(-Q_c / RT) \quad (9)$$

where the value of Q_c/R corresponds to the slope of the line and $\ln B$ to its intersection with the Y-axis. Q_c represents the apparent creep activation energy of

the material at the temperature and stress condition employed in the experiments. Linear regression was used for 12 sets of data like this, namely: five at 120 MPa, four at 180 MPa and three at 240 MPa. Twelve pairs of data of Q_c and the pre-exponential factor B were determined in this way, in the different creep strain levels for each stress level.

Figure 9b shows the plot of $\ln B$ as function of Q_c . It is interesting to notice that the data appear well aligned in each stress level so that they can be represented by straight lines approximately parallel to each other. This kind of pattern along three different lines seems natural since the factor B contains the term with the potential dependence on stress. To eliminate this dependence, and make the lines collapse into a single straight line, it is necessary to express the data in terms of the Dorn constant A , that is dimensionless and independent of stress.

The Dorn equation can also be expressed in the following way:

$$\dot{\epsilon}_s = A \cdot [D_0 \exp(-Q_c/RT) G b] / (kT) \cdot (\sigma/G)^n \quad (10)$$

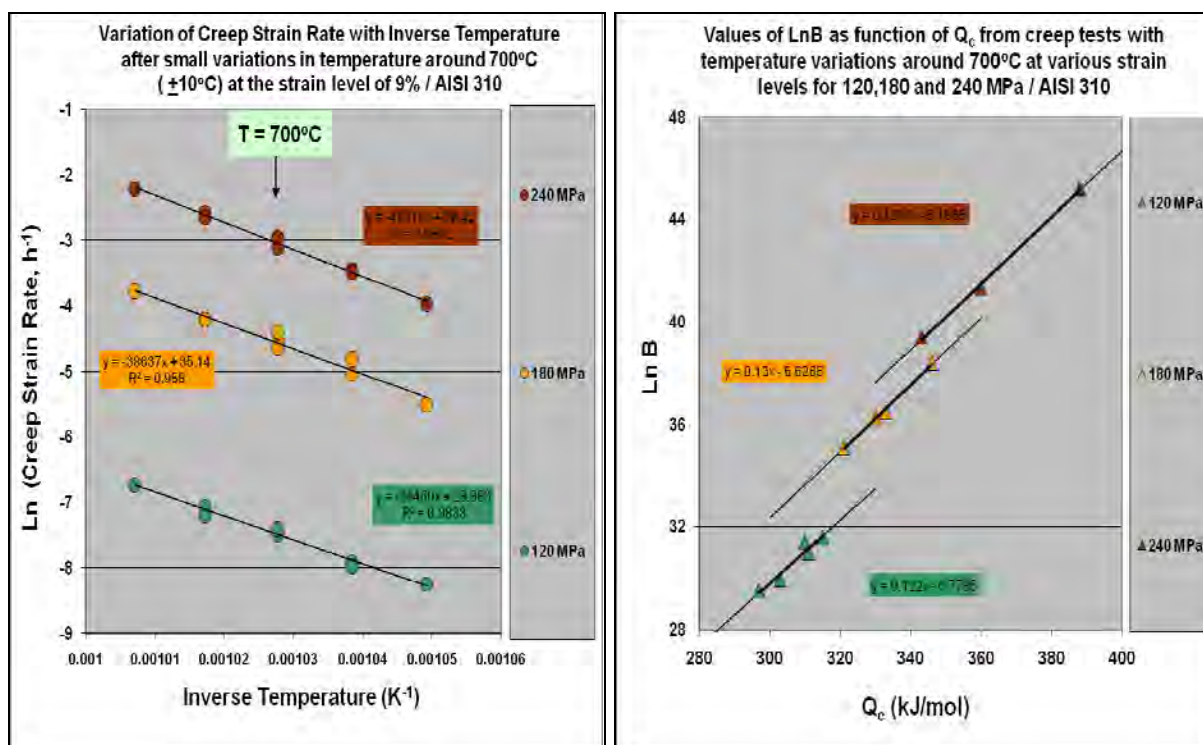


Figure 9 – a) Example of Creep Strain Rate data as function of Inverse Temperature after small changes in temperature ($\pm 10^\circ\text{C}$) around 700°C at the strain level of 9%, for 120, 180 and 240 MPa; **b)** Values of $\ln B$ as function of Q_c at various strain levels, for 120, 180 and 240 MPa.

It is possible to express the Dorn constant A in terms of the parameter B , by comparing of Equation 10 to Equation 9. And taking again: $D=3.436 \times 10^{-20} \text{ m}^2/\text{s}$; $G=55400 \text{ MPa}$; $b=2.58 \times 10^{-10} \text{ m}$; $k=1.381 \times 10^{-23} \text{ J/K}$; $T=973 \text{ K}$, the following relation is derived:

$$A = 7.058 \times 10^{-21} \cdot B \cdot (55400 / \sigma)^n \quad (11)$$

In the calculation of the values of A from the values of B it was necessary to estimate the values of n , at the three stress levels used in the tests. These data are available in section 3.1 of this article and also in the article relative of Part 1 of this work⁽⁹⁾. The 12 pairs of data involving the A and Q_c values are plotted in Figure 10a.

Linear regression of the data in this figure provides the following relation between LnA and \mathbf{Q}_c :

$$\text{LnA} = 0.113 (\mathbf{Q}_c - 71.53) \quad (12)$$

At this point, it is important to emphasize that Equation 12 was derived from the experimental values of \mathbf{n} and σ that were used in the calculation of \mathbf{A} from the values of \mathbf{B} , as shown in Equation 11. However, it must be noticed that a more correct relation between LnA and \mathbf{Q}_c would be obtained if, instead of the applied stress σ , the effective stress $\sigma_{\text{eff}} = (\sigma - \sigma_o)$ were taken into consideration in Equation 11. Also the values of the stress exponent \mathbf{n} should be taken as their values corrected for the effect of internal (or friction) stress. This kind of consideration regarding the effect of friction stress on creep behavior of AISI 310 was discussed in great detail in the article in Part 2 of this work.⁽¹⁰⁾

For the present analysis it is possible to consider a round value for $\sigma_o = 66$ MPa, for most of the data, since the stress levels used in the investigation (120 – 180 – 240 MPa) are all in the region where the friction stress shows a plateau of $\sigma_o = 66.3 \pm 2.2$ MPa, as presented in Figures 7a and 10b of Part 2 of this work⁽¹⁰⁾. However, the value of $\sigma_o = 66$ MPa was determined for secondary creep stage. Most of the 12 points in Figure are certainly satisfying this condition. Maybe, the only objection, could be with two points that were included in the analysis referring to data obtained at creep strain levels of 2% and 5% at the stress level of 120 MPa, since they could still be in the primary stage, and friction stress could not have had time to increase from the initial value $\sigma_{\text{oin}} = 6$ MPa to $\sigma_o = 66$ MPa in secondary stage. According to Parker and Wilshire⁽¹¹⁾ the friction stress increases fast asymptotically from σ_{oin} until its stabilization in σ_o at the secondary stage.

For the value of \mathbf{n} in Equation 1, it will be taken in consideration the work of Derby and Ashby,⁽⁶⁾ who proposed the incorporation of the internal or threshold stress in a “natural” potential law of creep with stress exponent $\mathbf{n} = 3$ for the determination of a correct relation between \mathbf{A} and \mathbf{n} .

Figure 10b illustrates the data of LnA plotted as function of \mathbf{Q}_c , considering $\mathbf{n} = 3$ and $\sigma_o = 66$ MPa. It is evident that the points show excellent linearity. The following relation could be fitted to the points: $\text{LnA} = 0.1130\mathbf{Q}_c - 8.0833$, which rearranged gives:

$$\text{LnA} = 0.136 (\mathbf{Q}_c - 269.0) \quad (13)$$

This is a result with high significance, never mentioned before in literature. It is remarkable that for $\mathbf{Q}_c = 269$ kJ/mol the value of $\text{LnA} = 0$, and therefore $\mathbf{A} = 1$. The value of $\mathbf{Q}_c = 269$ kJ/mol found in this analysis is very close to the value of activation energy for self-diffusion of iron in austenite, $\mathbf{Q}_{\text{sd}} = 270$ kJ/mol, and even to the value $\mathbf{Q}_{\text{sd}} = 280$ kJ/mol for Types 304 and 316 stainless steels, mentioned by Frost and Ashby⁽²⁾.

In Figure 7, it is also relevant that when $\mathbf{n} = 3$ the value of $\text{Log A} \approx 0$, i.e. $\mathbf{A} = 1$.

Equations 8 and 12 are, in fact, analogous: in both cases $\mathbf{A} = 1$, when $\mathbf{n} = 1$ and $\mathbf{Q}_c = \mathbf{Q}_{\text{sd}}$. Whenever \mathbf{A} or \mathbf{Q}_c increase beyond these fundamental limits, the values of LnA also increase beyond zero ($\mathbf{A} > 1$), in a linear manner.

The higher apparent values that are measured for \mathbf{A} , \mathbf{n} and \mathbf{Q}_c arise due to the presence of internal stresses developed during the deformation process. If the levels of these internal stresses are determined, it is always possible to rationalize the data according to a fundamental creep equation, as suggested by Derby and Ashby:⁽⁶⁾

$$\dot{\epsilon}_s = A_o \cdot [(DGb) / (kT)] \cdot [(\sigma - \sigma_o) / G]^n \quad (14)$$

where $A_o = 1$, that could be named the fundamental Dorn Constant.

Finally, it is important to point out the difference in the approach adopted in the present work and that of Ashby and co-workers^(4,5,6). In their work, a linear relationship between $\ln A$ and n was discovered, by a survey on creep data obtained in *secondary stage* reported by various authors involving *more than 50 different materials*, as shown in Figures 1a and 1b and commented in section 1 of this article. In the present work, a similar linear relation between $\ln A$ and n is revealed by a *unique material*, i.e. the AISI 310 steel, when subjected to small stress variations at various levels of creep during tests, ignoring the so called *secondary stage*. Furthermore, a linear relation also exists between $\ln A$ and Q_c , as shown in Equation 13 and Figure 10b, at least for AISI 310 steel, when creep tested in the present experimental conditions.

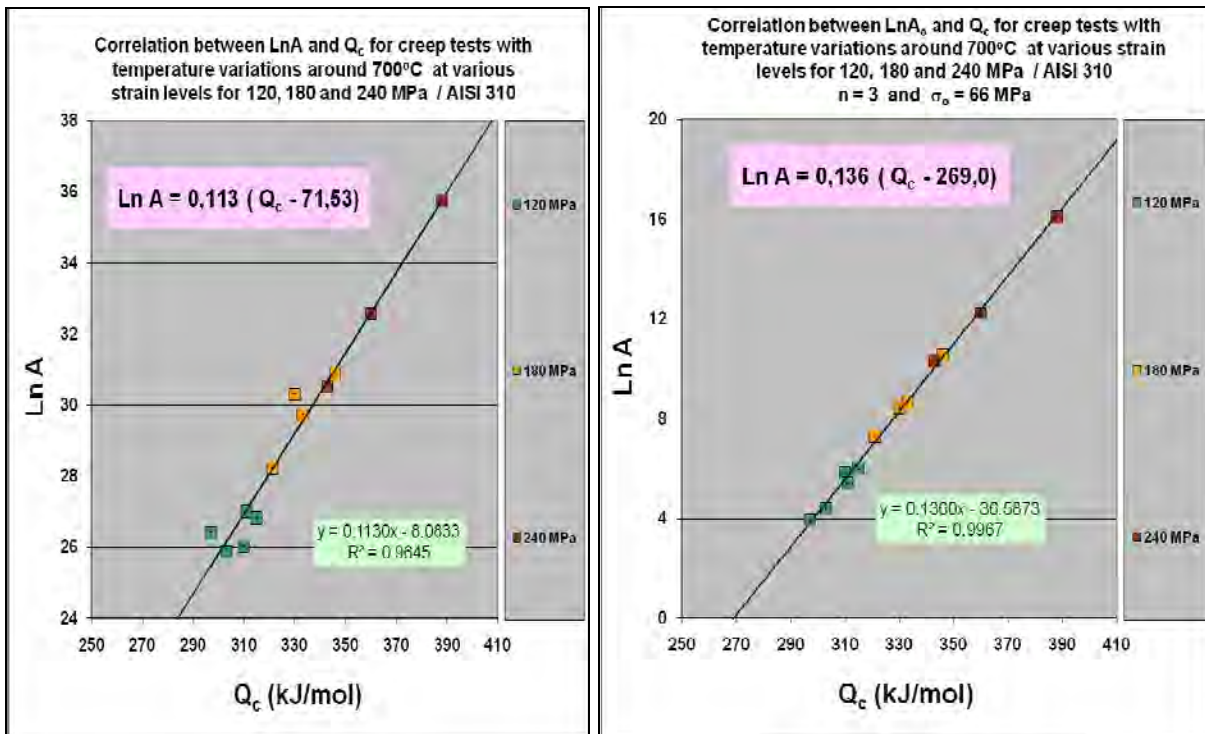


Figure 10 – a) Correlation between $\ln A$ and Q_c according to Equation 11 ; b) Correlation between $\ln A$ and Q_c , according to Equation 11, taking $n = 3$ and $\sigma_o = 66$ MPa.

5 CONCLUSIONS

- Data from creep tests in AISI 310 steel, at 700°C, in the range from 90 to 250 MPa, with small stress variation at six different points of the creep curves (involving primary, secondary and tertiary stages), revealed that a linear relationship exists between the Dorn constants A and the Norton exponents n , of the following type: $\text{Log} A = 2.46 (n - 2.87)$.
- This relation is very similar to those proposed by Stoker and Ashby⁽⁴⁾ and Brown and Ashby⁽⁵⁾ in the analysis of secondary creep data available in literature at that time, involving more than 50 materials.

- Data from creep tests in AISI 310 steel, at 700°C, in the range from 120 to 240 MPa, with small temperature variation at five different points of the creep curves (involving primary, secondary and tertiary stages), revealed that a linear relationship exists between the Dorn constants **A** and the Apparent Creep Activation Energy **Q_c**, of the following type: $\text{Ln} \mathbf{A} = 0.136 (\mathbf{Q}_c - 269.0)$, when the data are analyzed considering $n = 3$ and the effective stresses $\sigma_{\text{eff}} = (\sigma - \sigma_0)$, where $\sigma_0 = 66$ MPa, a value previously determined in Part 2 of this work⁽¹⁰⁾.
- The values $n = 2.87$ is very close to 3 and $Q_c = 269$ kJ/mol is very close to 270 kJ/mol, the self-diffusion activation energy for iron in austenite, considered as fundamental for creep deformation occurring by dislocation movement controlled by recovery processes.

The following conclusions can be advanced regarding the process of creep in general:

- The Dorn Equation can be used at all levels of creep strain, and not in the particular case of *secondary stage*, as considered by many authors.
- If the level of internal stress is known during the various stages of creep, it should be possible to determine creep strain rates by the equation:

$$\dot{\epsilon} = (\mathbf{D}G\mathbf{b}/kT) \cdot [(\sigma - \sigma_0)/G]^3.$$

- Values of $n > 3$ and of $Q_c > Q_{sd}$ happen when data of creep strain rate are analyzed in terms of the applied stress σ , without consideration for the effect of internal (or friction) stress in the process.
- If the effective stress is not considered in the analysis, values of **A**, **n** and **Q_c** follow linear relationships of the type:

$$\text{Log } \mathbf{A} = \alpha (\mathbf{n} - 3) \quad \text{and} \quad \text{Ln } \mathbf{A} = \beta (\mathbf{Q}_c - \mathbf{Q}_{sd})$$

where α and β are constants depending on the class of material in test.

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REFERENCES

- 1 SHERBY, O.D.; BURKE, P.M. Mechanical behaviour of crystalline solids at elevated temperatures. Progress in Materials Science, v.13, p.324-390, 1967.
- 2 FROST, H.J.; ASHBY, M.F. – Deformation Mechanism Maps – The Plasticity and Creep of Metals and Ceramics, Pergamon Oxford, 1982.
- 3 KASSNER M.E. and PEREZ PRADO M.T. Fundamentals of Creep in Metals and Alloys, San Diego, USA, 2004.
- 4 STOKER, R.L.; ASHBY, M.F. On the empirical constants in the Dorn Equation. Scripta Metallurgica, v. 7, p.115-120, 1973.
- 5 BROWN, A.M.; ASHBY, M.F. On the power-law creep equation. Scripta Metallurgica, v.14, p. 1297-1302, 1980.
- 6 DERBY, A.M.; ASHBY, M.F. Power-laws, and the A-n correlation in creep. Scripta Metallurgica, v.18, p.1079-1084,1984.

- 7 WALSER, B.; SHERBY, O.D. Structure Dependence of. Power Law Creep. Scripta Metallurgica, v.16, p.213-219, 1982.
- 8 SHERBY, O.D.; KLUNDT, R.; MILLER, A.K. Flow stress, subgrain size and subgrain stability at elevated temperature. Metallurgica Trans. A, v.8, p.843, 1977.
- 9 CONTIN JUNIOR, A.; BUENO, L.O. Creep Behavior on Type Behavior on Type 310 Stainless Steel. Part 1: Parameters from the Norton, Arrhenius and Monkman-Equation. To be presented in the 68th Annual Congress of ABM, Belo Horizonte, MG, July/August 2013.
- 10 BUENO, L.O.; CONTIN JUNIOR, A. Creep Behavior on Type Behavior on Type 310 Stainless Steel. Part 2: Analysis based on the study of transients after stress reduction experiments. To be presented in the 68th Annual Congress of ABM, Belo Horizonte, MG, July/August 2013.
- 11 PARKER, J.D.; WILSHIRE, B. Friction-Stress measurements during high-temperature creep of polycrystalline copper. Metal Science Journal, p.453, October 1978.