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CREEP BEHAVIOUR OF TYPE 310 STAINLESS STEEL. PART 2: ANALYSIS BASED ON THE STUDY OF TRANSIENTS AFTER STRESS REDUCTION EXPERIMENTS[1]

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Abstract

Stress-drop experiments during secondary creep in AISI 310 stainless steel were performed at seven stress levels in the range from 70 to 210MPa, at 700°C. Incubation periods were systematically detected following the stress reductions and their duration measured. Recovery kinetics parameters and friction stress (σ_o) data were determined by extrapolation using a physical equation suggested in literature for the process. The friction stress was found to increase linearly with applied stress in the range from 70 to 120MPa and to reach a constant value $\sigma_o \approx 66$ MPa from 120 to 210 MPa. The initial friction stress level of the material was also estimated to be about 6 MPa. Secondary creep rates could be expressed by a single power law relation with n ≈ 3.5 in terms of the effective stress ($\sigma - \sigma_o$). Initial creep rates could also be expressed by the same power law relation in the range from 40 to 140 MPa. Assumptions are put forward for the variation of the friction stress in secondary creep stage, in the interval from 250 to 375 MPa, so that secondary creep rate in the whole interval from 70 to 375 MPa can be expressed by: $\dot{\varepsilon}_s = 4.943\text{x}10^{-14}.(\sigma - \sigma_o)^{3.85}$. Normalization of the effective stress by the yield stress $\sigma_{0.05}$ of the material at 700°C, gives the relation: $\dot{\varepsilon}_s = 5.86\text{x}10^{-6}.[(\sigma - \sigma_o)/\sigma_{0.05}]^{3.85}$. This expression is not fully consistent with the universal equation proposed by Evans and Harrison for secondary creep in metallic materials.

Keywords: Type 310 stainless steel, stress drop experiments, creep transients.

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1 INTRODUCTION

Creep transients after stress variations during secondary stage have been extensively used as a technique for understanding fundamental deformation processes at high temperatures.[1,2] A number of different interpretation of this phenomena have been put forward by the various creep theories.[3] Analysis of high significance have been developed from the theory of dislocation network growth proposed in the past by McLean for the study of creep process.[4]
According to this model, a reduction in stress during secondary creep stage is always followed by a period of zero deformation rate, before the recommence of creep process under the action of the reduced stress. The theory considers that the processes which controls secondary creep rate is the growth of the tri-dimensional dislocation network developed within the subgrains (recovery process) until dislocation segments of sufficient size are generated that can operate as sources.

The internal stress caused by the refinement of the network during the deformation processes is maintained virtually equal to the applied stress during the secondary creep stage. When a reduction is made in stress, the dislocation link size rests bellow the critical size for operation as sources at the new stress level. An incubation period is necessary for growth of the dislocation network to an adequate dimension to allow creep happen again under the effect of the reduced stress.

Davies et al.[3] have introduced in this model the idea of the existence of a stress level, named *friction stress*, $\boldsymbol{\sigma_o}$, which is related to the micro-structural state and the dislocation substructure developed by creep on the material. This stress arises from the back stress effect to the applied stress, so that the creep deformation does not occur under the effect of the total applied stress, $\boldsymbol{\sigma}$, but under the effect of an effective stress, given by the difference between the applied stress and the friction stress, i.e. under $\boldsymbol{\sigma_{eff} = \sigma - \sigma_o}$. In this interpretation, the dislocation links in the network remain inactive most of the time, waiting until recovery enables them to glide. This means that *locally* the dislocation network is under the effect of an internal stress that equalizes the applied stress. The friction stress results from the population of dislocations that are immobilized in the substructure and act on the segments that are able to glide, establishing the *average mesh size* of the dislocation network.

One of the most significant aspects of this approach is the simplification for understanding the behavior of complex alloys which when analyzed in terms of $(\boldsymbol{\sigma - \sigma_o})$ start to exhibit stress exponents of the order of 3 to 4 (which are typical of pure metals and simple solid solution alloys) and apparent creep activation energies, $\mathbf{Q_c}$, very close to the activation energy for self-diffusion of the base metal.[3] This kind of analysis also makes possible the elimination of inflection regions on graphs of $\mathrm{Log}(\dot{\boldsymbol{\varepsilon}}) \times \mathrm{Log}(\sigma)$, or $\mathrm{Log}(\sigma) \times \mathrm{Log}(\mathbf{t_r})$, when the material exhibits two or more stress exponents at different stress ranges.

The technique that have been more employed to determine friction stress consists in the progressive reductions in stress at the secondary creep stage. In these experiments the applied stress is progressively reduced by decrements, $\Delta\sigma$, of the order of 5 to 10% of the initial applied stress. After each reduction, observation is made of the corresponding incubation period and, as soon as creep recommences, a new reduction is made, and so successively, as shown in Figure 1. The duration of the incubation periods gets longer and longer, as the number of reductions increase. When a reduction is made that produces a very long incubation period (in general of the order of various tens of hours), the applied stress remaining in the creep

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specimen could be considered as the friction stress for that temperature and stress conditions applied in the creep test. A plot of the cumulative stress decrements **ΣΔσ** versus **ΣΔt** shows that the reduced stress $\sigma_r = \sigma - \Sigma\Delta\sigma$ tends assymptoticaly a to limit value when ΣΔt tends to infinity.

The consideration of a *very long* incubation period in this procedure, however, seems ambiguous. McLean[1] proposed a method for the analysis of results from stress drop experiments which is based on a more accurate approach for the determination of σ_o. His procedure is based on equations related to the kinetics of growth of the dislocation links in the tridimensional network. An expression is derived that relates the incubation periods (Δt), the initial applied stress (σ) , the residual stress (σ_r), and the friction stress (σ_o), in the following way:

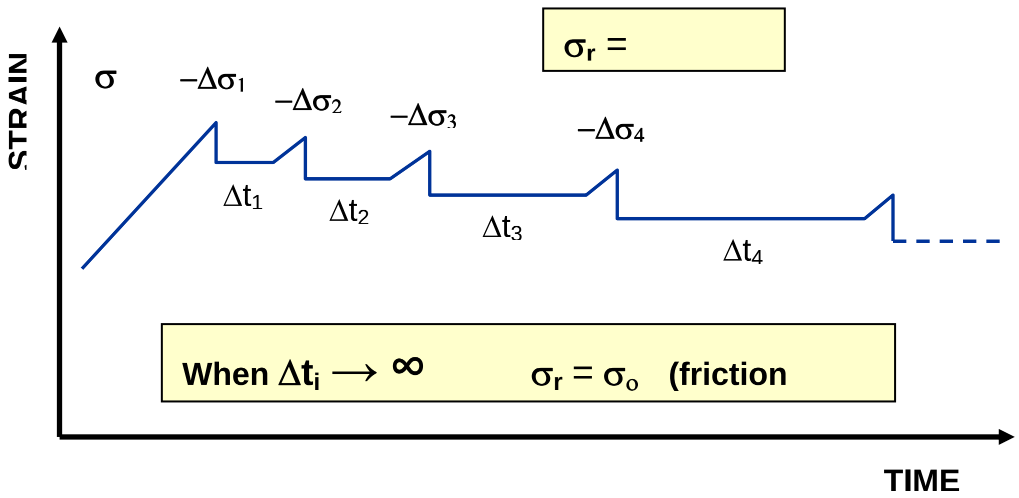

Figure 1 – Schematic representation of transients with incubation periods in experiments of progressive small stress drop during a creep test.

$$\Sigma\Delta t = (Gb)^m / K). [(\sigma_r - \sigma)^{-m} - (\sigma - \sigma_o)^{-m}] \qquad (1)$$

where **m** is an exponent connected to the mechanisms that control the growth of the links in the network, **G** is the shear modulus, **b** the Burgers vector and **K** a factor that involves parameters related to the network growth kinetics, showing a temperature dependence controlled by the sum of the activation energies for self-diffusion (Q_{sd}) and jog formation (**Uj**).

According to McLean,[1], **m** takes digit values varying from 2 to 5, according to the mechanism controlling creep. For **m** = 2, 3, 4 or 5 the control refers to: jog formation on dislocations, intragranular volume diffusion, grain boundary diffusion and dislocation pipe diffusion, respectively. McLean[2] remarks that the best fit with Equation 1 happens in most cases with m = 2 and 3 and proposes the use of m = 2 as adequate for determination of σ_o by a least square procedure of fit of his equation to data of **ΣΔσ** versus **ΣΔt**.

When $(\sigma - \sigma_o) >> (\sigma_r - \sigma)$, i.e. for incubation periods in a region close to the friction stress, the following simplified equation can be used to analyze the data and determine σ_o :

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$$\Delta t^{-1/2} = (Gb/K)^{1/2}.\,(\sigma_r - \sigma_o) \qquad (2)$$

The plot σ_r versus $\Delta t^{-1/2}$ is linear in this region and the line intercepts the stress axis at the value $\sigma_r = \sigma_o$. However, the reliability in this extrapolation procedure depends on the linear regression over the data in this region which may consist of few experimental points, since in general, as σ_r approximates σ_o, the greater the difficulty in detecting the incubation periods.

Evans and Harrison[(5)] verified, for a great variety of metallic materials, that by normalizing the effective stress by the yield stress at the test temperature, the data from various temperature levels collapse into a unique straight line when plotted in graphs of type Log $\dot{\varepsilon}_s$ x Log[$(\sigma - \sigma_o)/\sigma_{0.05}$]. Based on these results Evans and Harrison[(5)] proposed the existence of an universal equation for creep rates at secondary stage in the following way:

$$\dot{\varepsilon}_s = B.\,[\,(\sigma - \sigma_o)/\,\sigma_{0.05}\,]^{3.5} \qquad (3)$$

where **B** is a constant independent of the material and test temperature, having the value **B** = $2.73 \times 10^{-5}\ s^{-1}$.

However, it is important to emphasize that other interpretations have been put forward for transient behavior by the different creep theories, and that this subject was matter for a lot debate in literature until the '90s.[(6)]

The analysis of creep transients is very controversial, and in general it gets more complicated when the sensitivity of the instruments is not sufficient to resolve all the details involved in the phenomena, or when spurious effects interfere with measurements leading to false indications.[(7)]

Part 1 of this work[(8)] indicated that for a AISI 310 steel at 700°C in the range from 70 to 375 MPa the secondary creep rates are expressed by potential law with exponent **n** = 4.5 for stresses σ <130 MPa and **n** = 7.1 for stresses σ >130 MPa.

The present work presents an analysis of creep behavior of this steel based on friction stress measurements by progressive stress drop experiments to rationalize the data of initial creep rates and secondary creep rates as function of applied stress in the material. An attempt is also presented to correlate the data in the form of the universal equation proposed by Evans and Harrison for secondary creep stage creep rate.[(5)]

A preliminary article on the present subject was already published some time ago by the same authors.[(9)] A set of new data were added to the original results and a more extensive analysis is presented on the subject in the present article.

2 MATERIALS AND METHODS

Details of state of the material, chemical composition, grain size, specimen preparation and creep test techniques, etc were presented in Part 1 of this work[(8)]. All creep tests were carried out under *constant stress* condition, by use of an Andrade-Chalmers profile connected to the load-lever. Seven tests with progressive reduction of stress were carried out when the secondary creep stage was established, with the following applied stresses: 70 – 90 – 120 – 140 – 160 – 180 – 210 MPa, at 700°C. Stress drop tests at higher stress levels were not explored in this work, due to the increasing difficulty that they present for determination of shorter

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and shorter incubation periods, after the stress decrements from the initial stress level. All stress reductions performed in this work were of about 5 to 10% of the initial applied stress.[3] The incubation periods were measured by using creep extensometers attached directly to the specimens associated to LVDT-HP transducers and a chart recorder type x-t. In various situations a dial-gauge was also employed adapted to the edge of the load-lever. This arrangement was shown to be very useful, allowing sensitivities of strain readings of about $2x10^{-6}$, with good stability for observation of longer incubation periods (of about hours and tens of hours), which in general are disguised by the electronic instability effects at the resolution level conferred by the combination LVDT – chart recorder.

A program of non-linear curve fitting by iterative least-square technique was employed in the analysis of the incubation period data, according to Equation 1.

3 RESULTS AND DISCUSSION

The tests with progressive stress reductions have presented invariably the occurrence of incubation periods in AISI 310 steel. The duration of these periods have shown the normal trend of increase with the number of stress reductions applied in every experiment and their duration varied from about 20s up to 70h at the highest and lowest stress levels, respectively. Figure 2 shows an example of a sequence of incubation periods detected with the graphical recorder x-t after a sequence of stress reductions of 4.45 MPa, from an initial applied stress σ = 160 MPa during secondary creep stage. In this case, reduction of only 3% of the applied stress were accomplished and the incubation periods could be observed with a strain resolution of $5x10^{-5}$ at the recorder's chart. This kind of record, however, was not always obtained, since as the level of stress decreases, the distinction of re-start of the creep process gets more and more difficult, since the periods can last for hours. In various cases, it was necessary to increase the resolution level beyond the value indicated in Figure 2. When this happened, however, the chart recorder indications could become seriously affected by various kind of interference, such as: room-temperature variation, thermal fluctuations in the furnace, and mainly electronic instability from the strain measuring system itself. In these cases, as mentioned before, the dial arrangement at the load-lever offered more consistent readings, probably for not suffering the problems of electronic interference, with the disadvantage, however, of not allowing an automatic registration of the transients and incubation periods.

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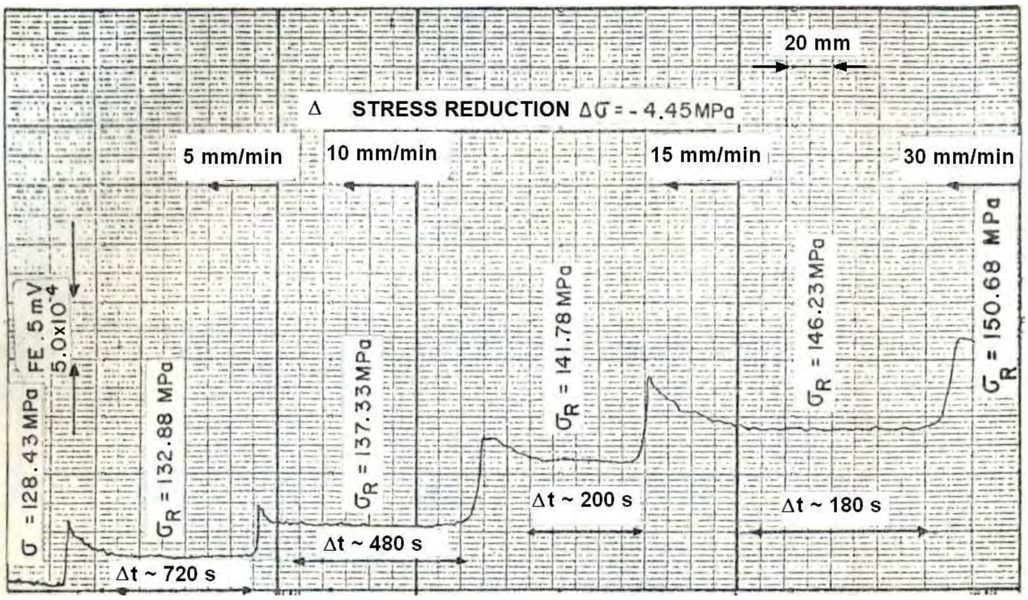

Figure 2 – Example of a series of incubation periods detected with a graphical recorder type x-t in progressive small stress drop during a creep test.

A probable interference of the anelasticity phenomena was observed on the creep transients, mainly during the experiments carried out at the lowest stress levels, or after the reductions that brought about longer incubation periods. The observation of anelastic contribution just after the recovered elastic strain could be detected mainly with the help of the dial-gauge arrangement. This effect produced a very small negative strain, of the order of about 50×10^{-6} at maximum. Due to the difficulty of automatic registration of the re-start of creep process, the incubation periods in these cases were considered as the time elapsed from point A to B, as indicated in Figure 3.

Figure 4 presents an attempt of analysis using the simplified equation of McLean (Equation 2), with data from the test with stress reduction from 180 MPa. Since, in the case of this experiment, various points were obtained in the region of saturation of the curve σ_r versus $\boldsymbol{\Sigma\Delta t}$, a linear extrapolation of values σ_r when $\boldsymbol{\Sigma\Delta t^{-1/2}} \rightarrow 0$ was viable, to determine the value of σ_o. However, this procedure was not always possible for the tests at the lower stress levels, since a more reduced number of data is obtained in the region where extrapolation must be applied.

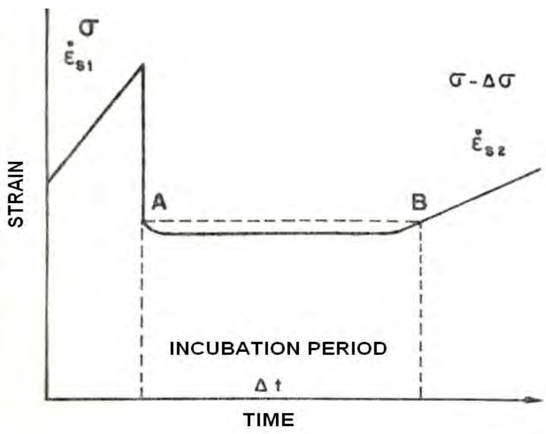

Figure 3 – Procedure adopted for determination of the incubation period in creep transients with the interference from anelasticity phenomena.

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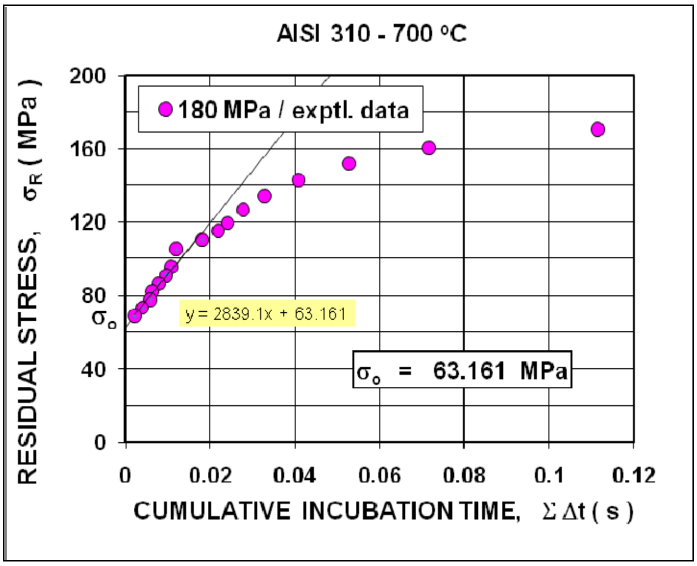

Figure 4 – Determination of the Friction Stress using the Simplified Equation of McLean (Equation 2).

Figure 5 presents the results obtained with the fit of Equation 1 to the all the data obtained with the experiments of stress reduction. In this analysis, a value of m = 2 was assumed. Figure 6 shows some examples of determination of friction stresses from different stress levels with the curve fitting program mentioned in section 2. In the case of σ = 180 MPa, for instance, the value of friction stress was σ_o = 62.976 MPa. This value agrees very well with the result obtained for friction stress using the simplified equation of McLean (Equation 2), where n = 63.161 MPa.

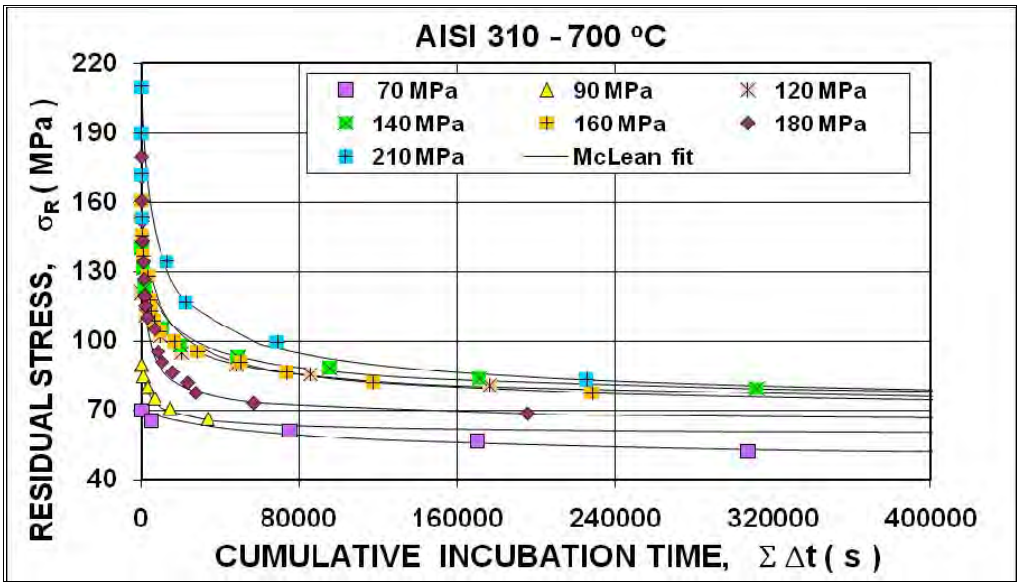

Figure 5 – Data of variation of the Residual Stress with the Cumulative Incubation Time, fitted with McLean function (Equation 1) involving the kinetics dislocation network growth under stress variation.

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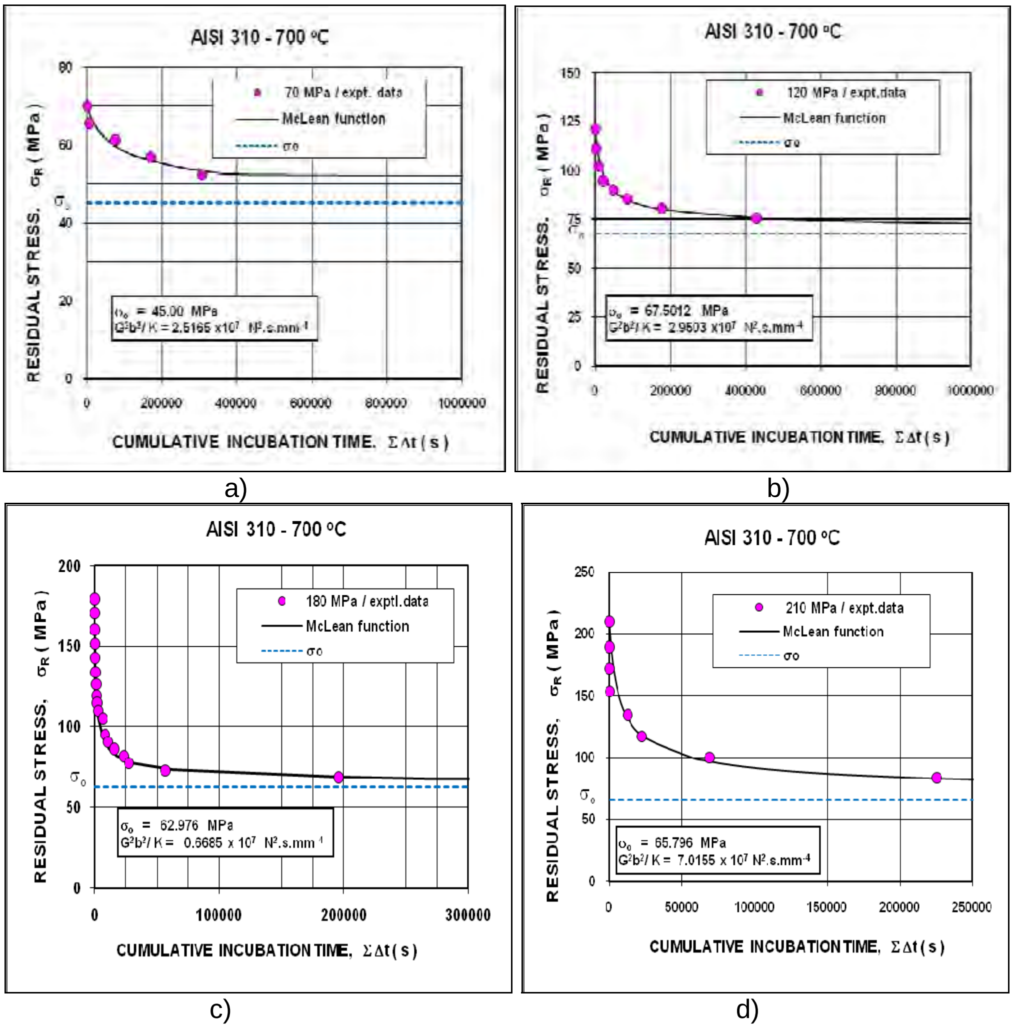

Figure 6 – Some examples of determination of friction stresses for different levels of applied stress.

Figures 5 and 6 demonstrate that Equation 1 present a satisfactory fit to the experimental data. The extrapolated results for σ_o agree well with McLean's result[(1)], who observed that the vales determined by using Equation 1 are in general 10 to 15% lower than those determined by the use of experimental data of stress reduction only, i.e. taking in consideration only the last reduction with the longest incubation period, as suggested by Wilshire et al.[(3)]

Figure 7a shows the variation of friction stress as function of the initial applied stress in the experiments. It can be noticed that this set of data can be expressed by two straight lines, as mentioned by Evans and Harrison[(5)] and Henderson and McLean.[(10)] Below approximately 120 MPa the values of σ_o present a trend to decrease with the applied stress. Above 120 MPa the values of σ_o can be considered as constant approximately, considering the magnitude of experimental errors that are typical in these kind of experiments.[(5)] This result is very similar to those reported by several authors that have measured friction stress in precipitation hardened alloys [(2)]. It is noteworthy that the transition in Figure 7a happens at about the same stress level where the transitions in behavior of initial and secondary rate happen. Figure 7b presents the variation of the Kinetic Factor **K** of Equation 1 with the applied stress. The data exhibit some scatter, but it seems to indicate that **K** increases slightly as the stress increases in the interval investigated.

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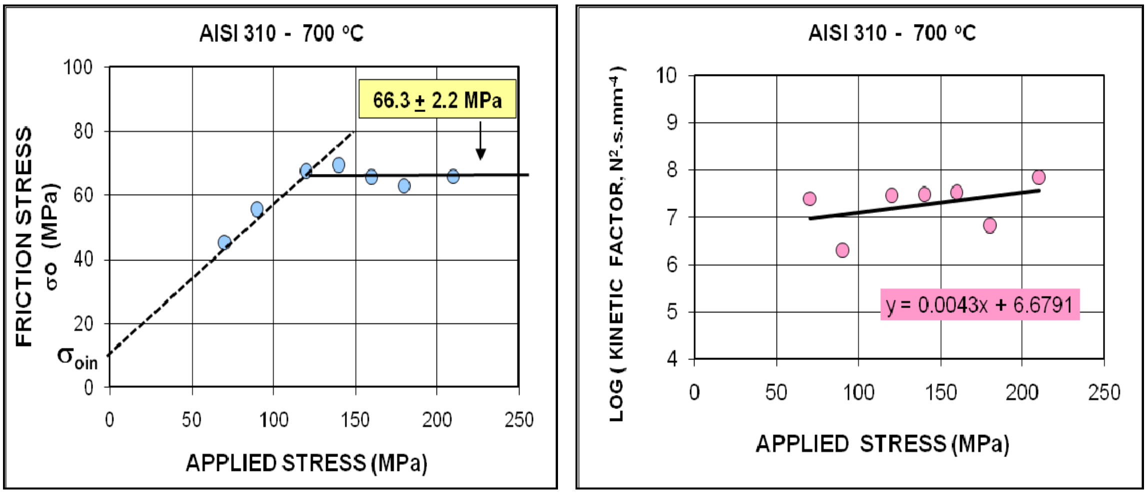

a) b)

Figure 7 – a) Variation of the values of Friction Stress (σ_o) with Applied Stress (σ) during secondary creep. Extrapolation of the first 3 points to $\sigma = 0$ gives the approximate value of the Initial Friction Stress (σ_{oin}) of the material); b) Variation of the values of the Kinetic Factor $\mathbf{K_c}$ with Applied Stress during secondary creep.

Figure 8 shows the variation of the Initial Creep Rates and Secondary Creep Rates with Stress. This figure was imported from the article presented in Part 1 of this work. It is interesting to notice that the Initial Creep Rate exhibits the same kind of inflection that was noticed with the Secondary Creep Rate data, at a stress level of about 130 MPa. For the Initial Creep Rates, when stresses vary from 40 to 130 MPa the stress exponent is $\mathbf{n_{in}}$ = 3.9 and when stresses vary from 130 to 375 MPa, $\mathbf{n_{in}}$ = 6.3. For Secondary Creep Rate, when stresses vary from 70 to 130 MPa the stress exponent is $\mathbf{n_s}$ = 4.5 and when stresses vary from 130 to 375 MPa, $\mathbf{n_s}$ = 7.1.

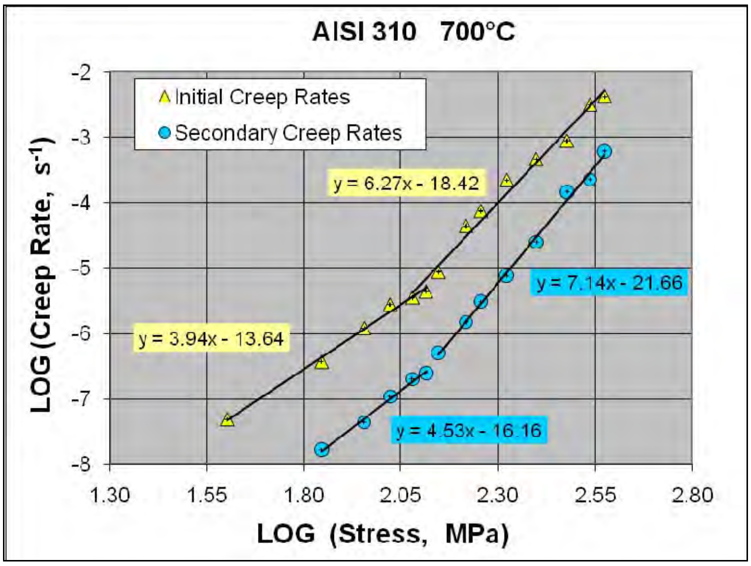

Figure 8 – Variation of Minimum Creep Rate and Initial Creep Rates with Stress , showing inflection at $\sigma \approx$ 120 MPa with two Norton exponents in both cases.

Figure 9a presents the data of the experiments of reduction of stress, where the variation of secondary creep rate was plotted against the effective stress

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$\sigma_{eff} = (\sigma - \sigma_o)$ instead of the applied stress σ. It is observed that the data can be expressed by a straight line with excellent correlation, with a single stress exponent **n** ≈ 3.4 in the range from 70 to 210 MPa. This result is similar to the results obtained by many authors who applied this kind of analysis to data from complex alloys.[11]

The possibility of expressing the initial creep rates by Norton law with a single stress exponent was also investigated. Figure 7a suggests a value of 10 MPa for the initial friction stress in AISI 310 steel under investigation. This value was taken in the analysis and the result was reasonably satisfactory. However, it was noticed that a more adequate value for the initial friction stress for a better linearization of the initial creep rates was in fact σ_{oin} = 6 MPa. The result of variation of the initial creep rates with the initial effective stress $\sigma_{eff\ in} = (\sigma - \sigma_{oin})$ is shown in Figure 9b, together with the result of the secondary creep rates (Figure 9a), for comparison. It is highly significant that the two sets of data can be expressed by the *same* linear relation, with a single Norton exponent **n** = 3.5. This means that basically the same creep process is happening for the initial creep stress and secondary creep stress in the stress range from 70 to 210 MPa. The low value of 6 MPa for AISI 310 agrees well with values of σ_{oin} mentioned in literature for other materials.[10,11]

According to several authors [1,2,10,11] the friction stress is predicted to present a continuous decline after a certain level of stress tending to zero at the highest stress levels the material can support. Measurements of friction at high applied stress levels have confirmed this idea[11] and linearization of the data with a single stress exponent has been possible in a broad stress range, including high stresses. Although experiments of friction stress could not be carried out at the stress levels of 250 – 300 – 344 – 375 MPa, in the present work, there was an interest in rationalization of the results also in this stress range. For the applied stress of 250 MPa, it was verified that the respective data could be linearized with the same value of the plateau in Figure 7a, i.e. σ_o= 66.3 MPa. However, for the other three points (300, 344, 375 MPa), the value of σ_o= 66.3 MPa is inadequate for linearization of the results. The best possibility of linearization of these three points occurs if the following values of friction are assumed: ~40 MPa,~20 MPa and Zero MPa, respectively. Figure 10a presents the result of this analysis demonstrating that the relation $\dot{\varepsilon}_s = 4.943\times10^{-14}.(\sigma - \sigma_o)^{3.85}$ is valid for the whole interval from 70 to 275 MPa. Figure 10b illustrates the general pattern of variation of friction with applied stress.

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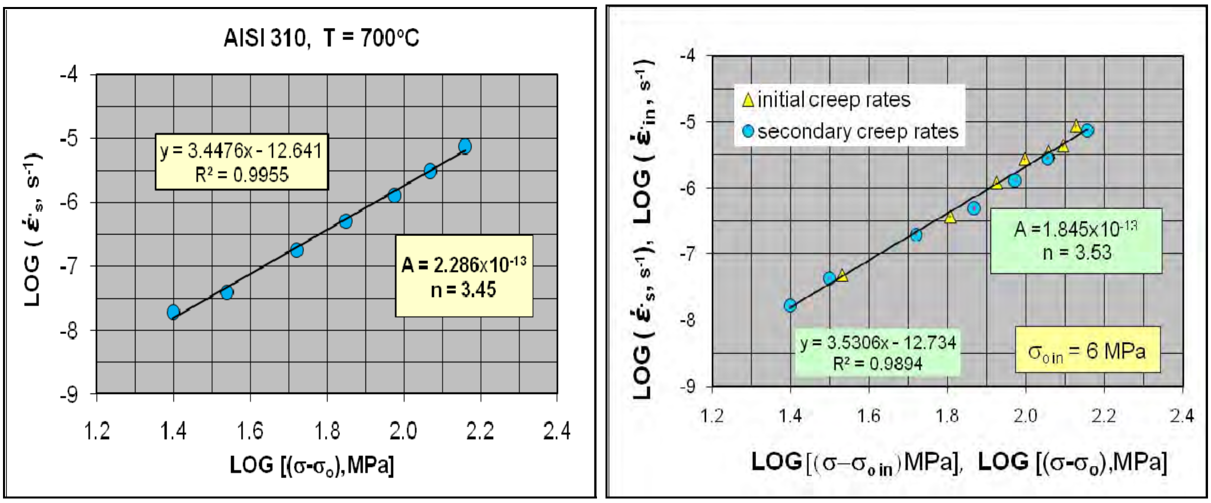
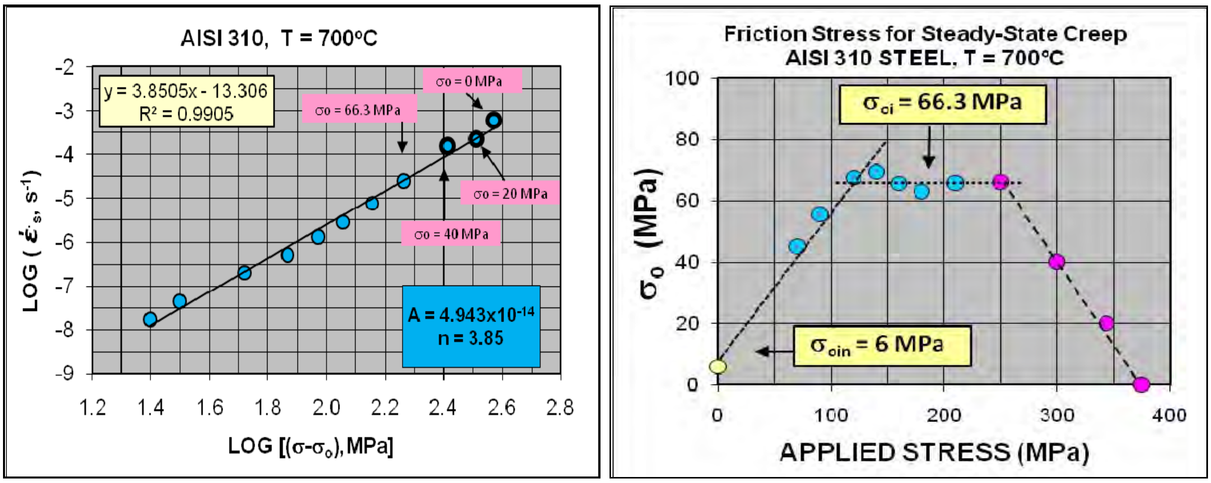


a) b)

Figure 9 – a) Rationalization of the Secondary Creep Rates in the range from 70 to 210 MPa, using the Effective Stress (σ- σ_o). The inflection shown in Figure 5 disappears, and a single value for the stress exponent (**n** ≈ 3.4) holds in this stress range; b) Rationalization of the Initial Creep Rates in the range from 40 to 140 MPa, using the Effective Stress (σ- σ_{oin}), taking σ_{oin} = 6 MPa. The two sets of data can be expressed by a single straight line (with **n** ≈ 3.5).



a) b)

Figure 10 – a) Rationalization of the Secondary Creep Rates in the range from 70 to 375 MPa, using the Effective Stress (σ- σ_o) using the values for σ_o mentioned in the graph, for stresses in the range from 250 to 375 MPa. The inflection shown in Figure 5 disappears, and a single value for the stress exponent (n ≈ 3.8) holds in the whole stress range; b) Proposed variation for the Friction Stress (σ_o) with Applied Stress.

It is important to mention that the points represented in blue color correspond to the data obtained in the friction stress experiments. The point in yellow color correspond to the value of σ_{oin} = 6 MPa (best value for linearization of the data of initial strain rates from 40 to 140 MPa, in coincidence with the secondary creep data). The points in red color represent the values of stress friction deduced for occurrence of best linearization of all secondary creep points from 70 to 375 MPa.

However, it was verified the impossibility of linearization of the data of initial creep rate in the region from 140 to 375 MPa using the value σ_{oin} = 6 MPa, as depicted in Figure 11. It is important to remind, as pointed out in Part 1 of this work, that the yield stress of AISI 310 in this study takes the value $\sigma_{0.05}$ = 125 MPa.

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The impossibility of linearization of the initial creep rate data for stresses greater than 140 MPa occurs probably because of the transition in the nature of the instantaneous deformation which happens at the time of loading the specimens in the creep tests. Below 125 MPa the instantaneous strain are predominantly elastic, whereas beyond 125 MPa the instantaneous strain exhibits both the elastic and plastic components, with the plastic component assuming more and more relevance with the increase in applied stress in the test. For stresses higher than 140 MPa, a massive number of dislocations start to move at the moment of loading, developing a dislocation structure that is radically different from that of the original material. Therefore, the initial creep rates measured in this stress range cannot be rationalized by the original friction stress of the material.

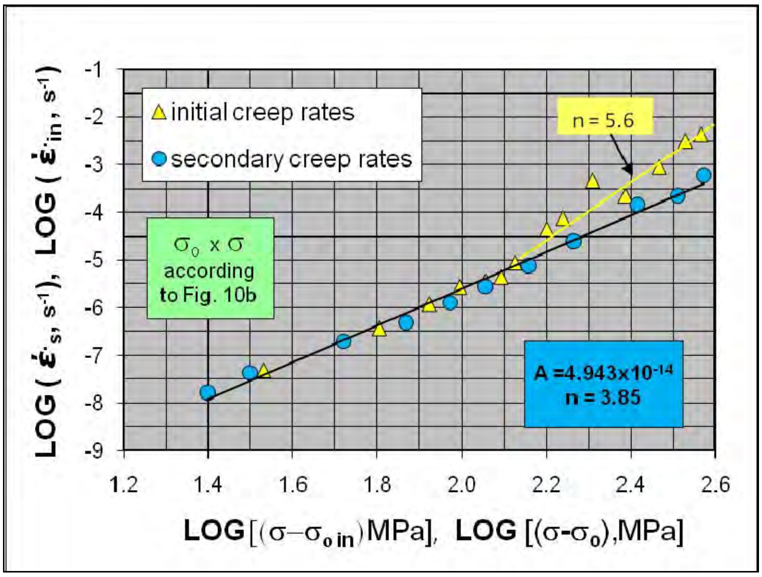

Figure 11 – Rationalization of the Initial Creep Rates and Secondary Creep Rates in the range from 70 to 375 MPa, using the Effective Stress (σ- σ_o) and (σ- σ_{oin}), respectively. The Secondary Creep Rates are fully rationalized by the effective stress. The Initial Creep Rates cannot be rationalized properly with the value of σ_{oin} = 6 MPa for stresses in the range from 120 to 375 MPa.

An attempt was also made to verify the validity of the universal equation proposed for Evans and Harrison,[5] for secondary creep rate as function of the effective stress normalized by de yield stress, $(\sigma - \sigma_o) / \sigma_{0.05}$, as remarked in section 1 of this article. The result is shown in Figure 11. Although the stress exponent of **n** ≈ 3.8 for AISI 310 agrees reasonably well with **n** = 3.5 in the universal equation, the value of parameter **B** is somewhat different: in the present work **B** = 5.86 x 10^{-6} whereas in the Evans and Harrison equation **B** = 2.73 x 10^{-5}, i.e. five times lower than the value proposed by the authors.[5]

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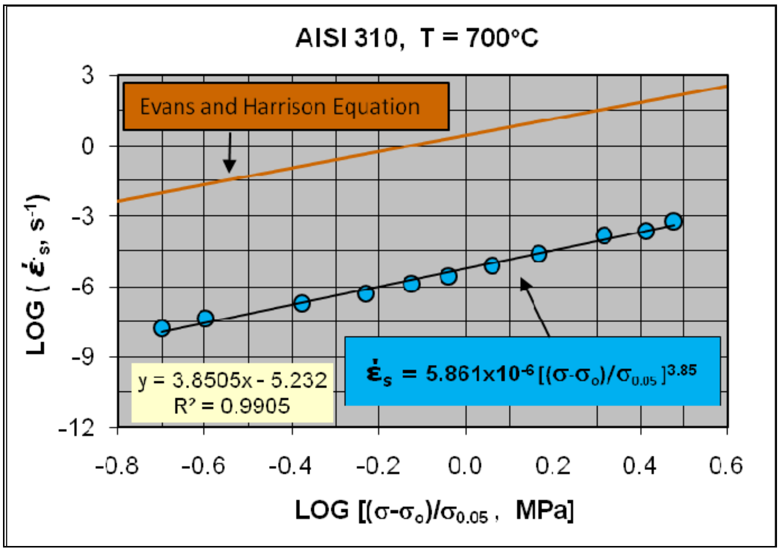

Figure 12 – Comparison of results of variation of Secondary Creep Rates in terms of the normalized effective stress for AISI 310 with the universal equation proposed by Evans and Wilshire [5].

4 CONCLUSIONS

- Incubation periods were systematically observed in all the experiments with progressive small stress reductions carried out in AISI 310, at 700°C, in the stress range from: 70 to 210 MPa, indicating that creep deformation in this material can be controlled by recovery process acting in the tridimensional dislocation network.
- These kind stress drop experiments demonstrated the existence of a level of friction stress (σ_0) for each applied stress value in the creep tests.
- The analysis of the data from the stress drop experiments have shown good consistency with the methodology of M.McLean based on the tridimensional network dislocation growth during creep.
- The secondary creep rates can be rationalized in terms of the effective stress considering the friction stress values experimentally measured, in the range from 70 to 210 MPa, in the form of a single straight line with stress exponent **n** ≈ 3.5.
- The initial creep rates can also be rationalized in terms of the effective stress considering an initial friction stress σ_{oin} = 6 MPa, in the range from 40 to 140 MPa, also in the form of a straight line with stress exponent **n** ≈ 3.5. The data of initial creep rate and secondary creep rate, analyzed in this way, become coincident.
- Assumptions are put forward for the variation of the level of friction stress, in secondary creep stage, with applied stress in the interval from 250 to 375 MPa. With these assumptions, the secondary creep rates can be expressed in terms of the effective stress, from 70 to 375 MPa, by the following expression:
  $\dot{\varepsilon}_S = 4.943 \times 10^{-14} . (\sigma - \sigma_0)^{3.85}$.
- The data of initial creep rates cannot be expressed by a single potential expression in terms of the effective stress, in the whole stress interval investigated, in the same way as happened for the secondary creep rates. Both data are coincident up to 140 MPa. For $\sigma > 140$ MPa, however, the initial creep rates exhibits an inflection with **n** = 5.6. This happens certainly due the increasing contribution of instantaneous plastic strain during the loading application in creep tests, at stresses higher than 140 MPa.

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- The data of secondary creep rate expressed in terms of the effective stress normalized by the yield stress $\sigma_{0.05}$ can be expressed by the relation:
  $\dot{\varepsilon}_s = 5.86\text{x}10^{-6}. [(\sigma - \sigma_o)/\sigma_{0.05}]^{3.85}$.
  This expression is not compatible with the relation proposed by Evans and Harrison: $\dot{\varepsilon}_s = 2.73\text{x}10^{-5}. [(\sigma - \sigma_o)/\sigma_{0.05}]^{3.5}$ as an universal equation for secondary creep in metallic materials.

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