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Study on Reloading Stress Relaxation Behaviour for High Temperature Bolted Steel

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Abstract. Designing and maintenance of mechanical elements is very important to clarify the effect of retightening (reloading) on stress relaxation behaviour of high temperature bolts. Experiments of stress relaxation simulates the real engineering problem of the long-term loosening of tightened bolts and other fasteners. Stress relaxation curves for a bolted steel 25 NiCrMo 8 are analyzed at three levels of test temperature (400, 450 and 500°C). The effect of the specified relaxation stresses on the reloading stresses behaviour is studied using five levels of the specified relaxation stress ratio (0.9, 0.8, 0.7, 0.6 and 0.5). Discussions are made on the relation between the testing time at each cycle and the number of loading with the variable of the specified relaxation stress ratio and the test temperature. The plastic strains accumulated during the course of the testing are analyzed and calculated by using empirical equation. Moreover, the apparent activation energy of relaxation behaviour which is determined as a relation of the testing time and of the specified relaxation stress ratio can be calculated.

Keywords: activation energy, loading number, plastic strain, specified relaxation stress, Steel 25 NiCrMo 8, stress relaxation, test temperature

I. Introduction

The steel 25 NiCrMo 8 is used in steam turbine as a bolting materials [1, 2]. The understanding of stress relaxation behaviour of structural materials is required for designing components [1–3]. Stress relaxation at high temperature is a problem in rivet and screw joints. This problem is also important for machine elements such as wheel, spring brackets and welded joints. In such joints there are three main types of stress relaxation [3, 4]:

1. the joint plates relax,
2. the screw threads in the alloy component relax;
3. the tread of the alloy screw relax.

Stress relaxation is the time and temperature depended decrease in stress in a solid, due to the conversion of elastic to plastic strain. Stress relaxation data can be used to develop stress-relief heat treatments for reducing residual stresses and for the design of such mechanical elements. Until 1960, stress relaxation was primarily of interest only to those concerned with the design and manufacture of steam and power generating equipment and, to a lesser extent those concerned with the design of gasket, reinforced concrete, and electric motors. Stress relaxation data are also an important tool for evaluating the constitutive relations governing a materials inelastic behaviour [3–10].

The effect of stress relaxation on residual stress of a wide variety of materials is discussed in many references [1, 4–13]. Sanchez-Galvez and Flices [8] predicted the stress relaxation from the results of the tension test and prediction of more complex processes under actual conditions, such as thermal cycling. Also they determined the relationship between tensile strain, creep and stress relaxation in cold drawn steels at low temperature.

This paper was initiated to determine the stress relaxation properties of 25 NiCrMo 8 steel at three levels of the test temperature 400, 450 and 500°C. The influence of the specified relaxation stress ratio on the plastic strain was examined. An empirical equation for the reloading stress relaxation was estimated on the basis of the data obtained.

II. Experimental procedure

II.1. Model formulation

An ideal stress relaxation tension test is shown in figure 1. A specimen of length (L) has a stress (σ) applied at time ($t = 0$), which elongates the specimen by a change in length (δ). Subsequently, the specimen is held at the same total length, and the stress (σ) decreases as a function of time (figure 2).

The stress-relation data have been derived from "Step-down", or interrupted creep tests.

Figure 3 shows the step-down creep test for a specimen subjected to a stress that causes an initial strain such as OA. The stress is applied as rapidly as possible without impact, and the maximum deformation is measured, after which an increment of load ($\Delta\sigma$) is removed. Upon removal of the stress, elastic recovery corresponding to AB occurs, but under the remaining stress ($\sigma_0 - \Delta\sigma$) creep is initiated and follows the path BC. When the total length is again equal to the original value L_0 $(1 + \varepsilon_i)$, a second increment of stress ($\Delta\sigma$) is removed.

Under this reduced stress, a somewhat longer time is required to deform the specimen to the original value L_0 $(1 + \varepsilon_i)$; that is, creep may now be assumed to follow the curve DE of figure 3(a) rather than the curve BC. By repetition of this procedure, data are obtained which, when plotted in the form of figure 3(b), will be approximate the stress relaxation curve.

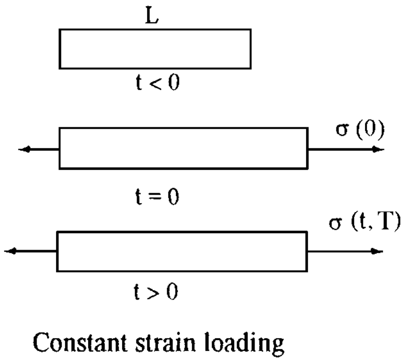


Figure 1. Ideal stress-relaxation test in tension.

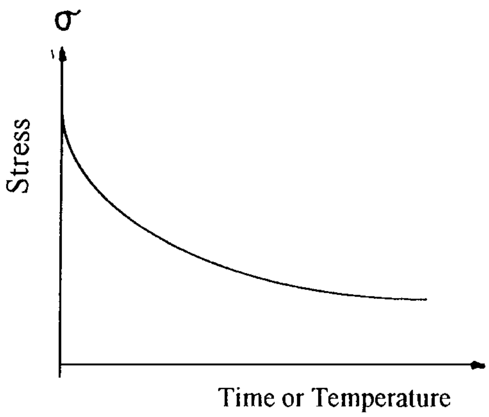
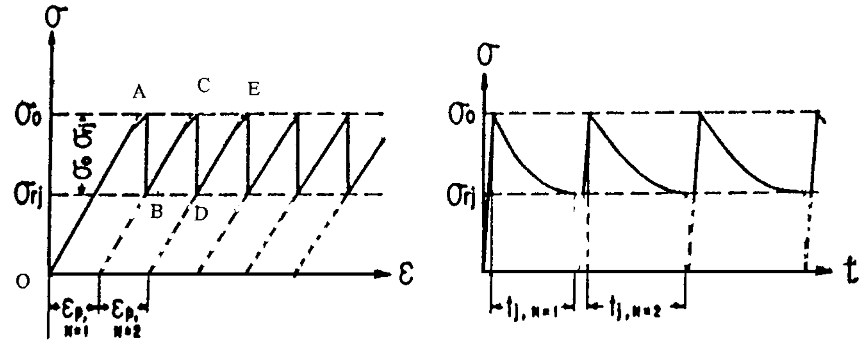


Figure 2. Tensile force as a function of time and temperature.



a. Constant extension approximate by step-down creep test.

b. Stress-time relation.

Figure 3. Derivation of stress-relaxation curve for step-down creep test.

II.2. Material

Polycrystalline specimens of a bolted steel 25 NiCrMo 8 were used in the present stress relaxation tests. Figure 4 shows the microstructure of the bolted steel by using optical microscope. The chemical composition and mechanical properties of the material used are given in Tables 1 and 2 respectively. The dimensions of the cylindrical specimens are 4.5 mm gauge diameter and 25 mm gauge length. The cross-sectional area of a specimen was measured with an optical micrometer within an accuracy of ±0.1%.

Table 1. Chemical of bolted steel 25 NiCrMo 8.

Element	C	Ni	Mn	Mo	Cr
Weight%	0.25	0.8	1.28	0.3	0.15

Table 2. Mechanical properties of the bolted steel 25 NiCrMo 8.

Temperature°C	σ_y (MPa)	σ_u (MPa)	δ (%)	q (%)
Room temperature	460	660	25	45
400	350	460	27	49
450	295	380	29	52
500	240	310	33	56

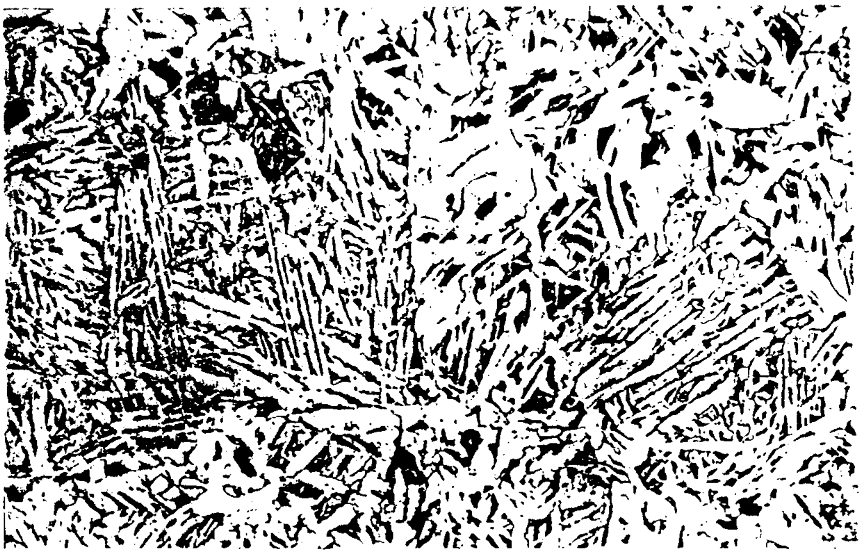


Figure 4. Microstructure of the bolted steel 25 NiCrMo 8.

II.3. Experimental testing

Stress relaxation tests were conducted with an tensile testing machine according to ASTM standard E238, "Stress Relaxation Tests for Materials and Structures", which specifies control of total strain on the test specimen within = 0.000025 mm/min. The test temperatures were 400, 450 and 500°C. The test temperature were controlled within ±0.5 k.

The effect of the specified relaxation stresses (σ_{rj}) on the reloading stress relaxation at one level of the test temperature (from five levels = 0.9, 0.8, 0.7, 0.6, 0.5 σ_0) were studied.

Repetition of the either of these load/unload/reload procedures yields data such as stress history, plastic strain, number of loading and testing time, from which the stress relaxation curve can be developed.

The values of the initial stress (σ_0) were those which were determined corresponding to the value of the plastic strains (ε_p). The values of (σ_0) depends on the test temperature and must be less than the yield strength. These values were equal to 300, 250 and 200 MPa at test temperatures of 400, 450 and 500°C respectively.

The reloading stress relaxation tests were started as soon as the initial stress had been applied to the specimen. The test was carried out until the stress (σ_{rj}) and the testing time (t_{j}) was observed. Then, unloading was carried out, and the value of the total strain was measured. After that, the load of the initial stress level was applied again. The test cycle composed of three factors: loading, unloading and reloading, was repeated up to twenty-five times. During the test, reloading stress relaxation, testing time, loading number and plastic strain were observed at each test temperature.

III. Results and discussion

III.1. Specified relaxation stress ratio

In example of the reloading stress relaxation curves when the stress (σ_{rj}) relaxed to the various specified value of relaxation stress ($S_{\mathrm{r}} = \sigma_{\mathrm{rj}}/\sigma_{\mathrm{o}}$) at temperature equal to 400°C are shown in figure 5. The curve at the first loading cycle ($N = 1$) is known a conventional stress relaxation curve, while after this curve ($N > 1$) are known as a reloading stress relaxation curves.

In this figure, it is clear that the testing time (t_{j}) at the specified relaxation stress ratio (S_{r}) increased with an increase in the loading number (N) until certain limit and then the testing time (t_{j}) start to decrease. This point is called inflection point and the testing time and loading number are known t_{jc} and N_{c} respectively. The similar trend of curves were observed when the specified relaxation stress ratio (S_{r}) changed.

III.2. Plastic strain

The relationship between accumulated plastic strains (ε_{p}) and loading number (N) for various specified relaxation stress ratio (S_{r}) is shown in figure 6. It is clear that there is a linear relation between (ε_{p}) and (N) at various value of specified relaxation stress ratio. The similar behaviour was observed at different test temperatures.

It was considered that the increase of stress relaxation test for constant total strain might be caused by shrinking of material, that is, thermal densification [3]. Plastic strain (ε_{p}) is a ratio of shrinking to original dimension. The shrinking of this material is linearly increases with increasing of loading number. The shrinking of material can be expressed

$$\varepsilon_{\mathrm{p}} = 4.5 \times 10^{-4}\,(S_{\mathrm{r}})^{-2.95}\,(N)^{b} \tag{1}$$

where b is the exponent depends on the test temperature. This exponent increases with increasing test temperature from about 0.98 at 400°C to about 1.07 at 450°C; at 500°C $b = 1.18$. The value of the b exponent can be expressed as

$$b = 0.17 + 0.002\,T\,(^{\circ}\mathrm{C}) \tag{2}$$

It is clear from figure 6 that, a very good agreement of the present experimental results and the empirical Eq. (1). The plastic strain increases with increasing of loading number and test temperature, while ε_{p} decreases with increasing of specified relaxation stress.

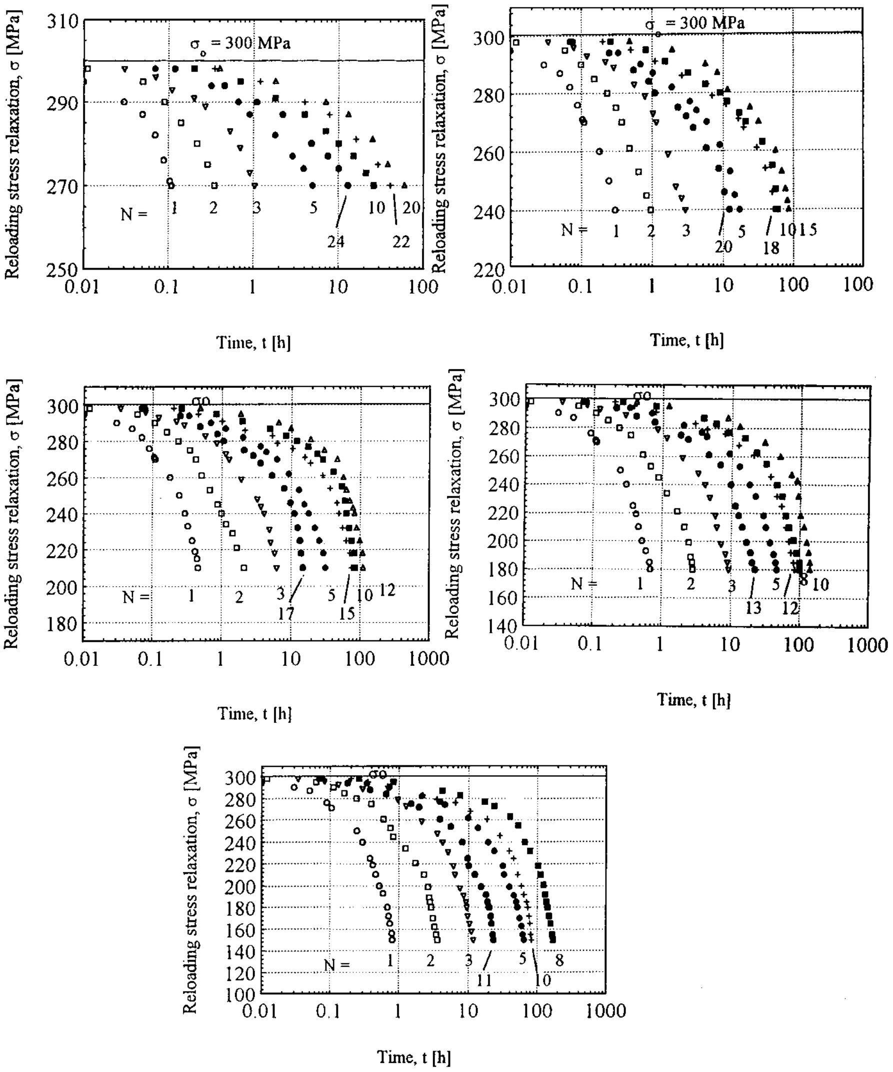


Figure 5. Reloading stress relaxation curve at 400°C for specified relaxation stresses of 0.9, 0.8, 0.7, 0.6 and 0.5 σ_0.

III.3. Cause of inflection

In order to analyze the reloading stress relaxation behaviour, the points of inflection at t_{ic} and N_{c} were to be important as a transitional point. Figure 7 is shown the relation between testing time and loading number for various specified relaxation stress ratio at 400°C. The values of testing time were increased to a certain limit then start to decreased sharply with increasing of loading number. The values of testing time were changed from an increasing trend to a decreasing one with increasing of loading number. A discussion on a cause of the inflection on testing time and loading number were made.

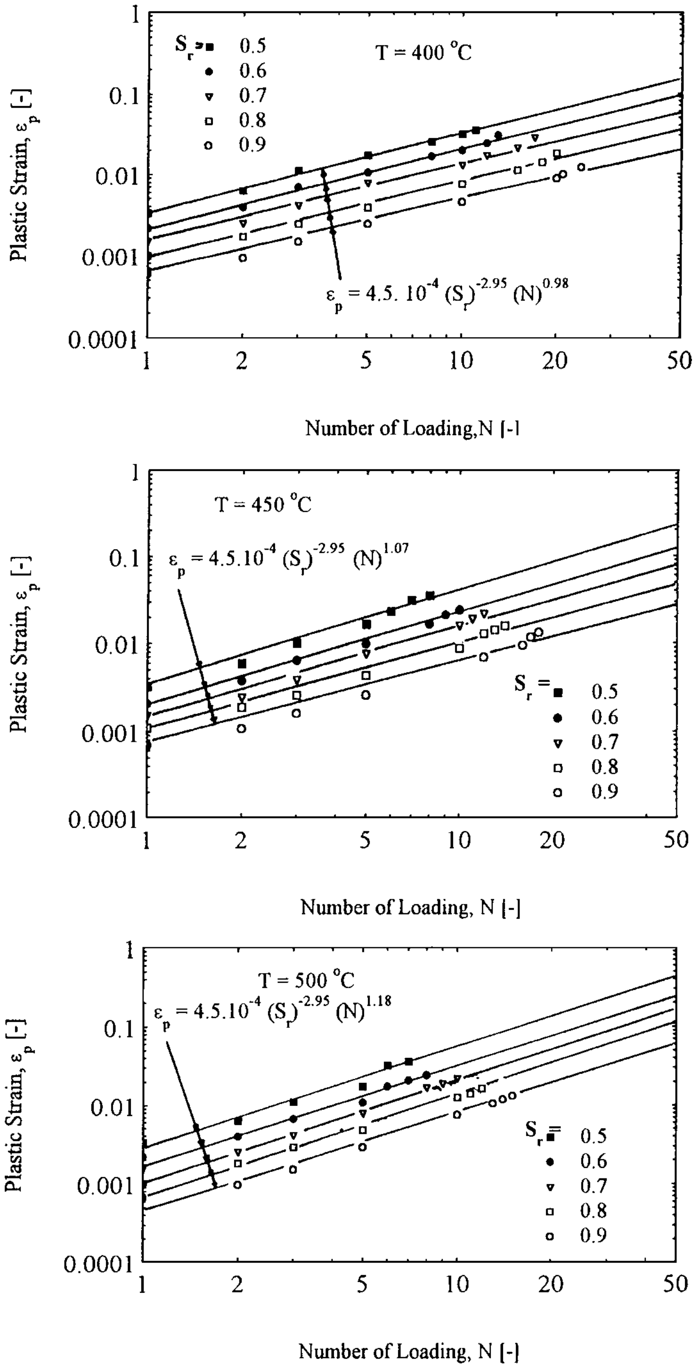


Figure 6. Relation between plastic strain and number of loading for various specified relaxation stresses at test temperatures 400, 450 and 500°C.

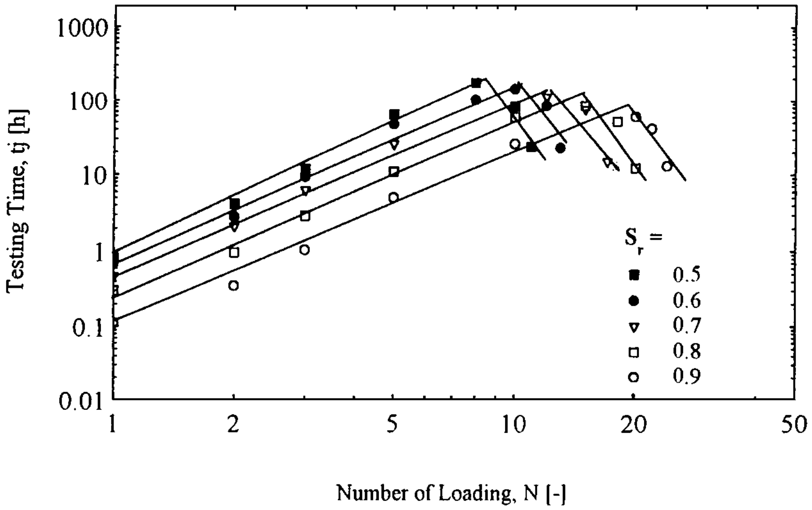


Figure 7. Relation between testing time and loading number for various specified relaxation stress ratio at 400°C.

III.3.1. Testing time. The logarithmic relation between inflection testing time (t_{jc}) and specified relaxation stress ratio (S_{r}) is shown in figure 8 at different test temperatures 400, 450 and 500°C. It is clear that the inflection testing time decreased with the increase of the specified relaxation stress ratio. As the data points were successfully laid on the regression line, it was proven that the whole data points in the log t_{ic} vs. N_{c} relation were represented by a straight line at different temperature.

III.3.2. Loading number. As example of the logarithmic relation between inflection loading number N_{c} at different test temperature and specified relaxation stress ratio (S_{r}) is shown in figure 9. In this figure it is clear that N_{f} increased with an increase of the (S_{r}).

III.4. Activation energy of relaxation

The temperature dependence on the testing time at constant applied stresses is shown in figure 10. The apparent activation energy (Q) for relaxation can be determined as the relation

$$t_{\mathrm{jc}} = B\left(\frac{\sigma_{\mathrm{r}}}{\sigma_0}\right)^{-m} \exp\left(\frac{Q}{RT}\right)$$

$$t_{\mathrm{jc}} = B(S_{\mathrm{r}})^{-m} \exp\left(\frac{Q}{RT}\right) \tag{3}$$

where m is the stress exponent and B is the material constant.

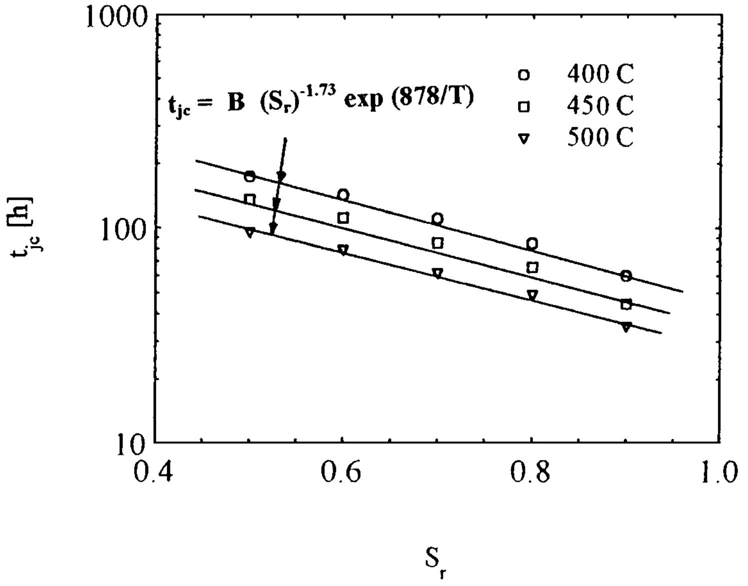


Figure 8. Inflection testing time vs. specified relaxation stress ratio.

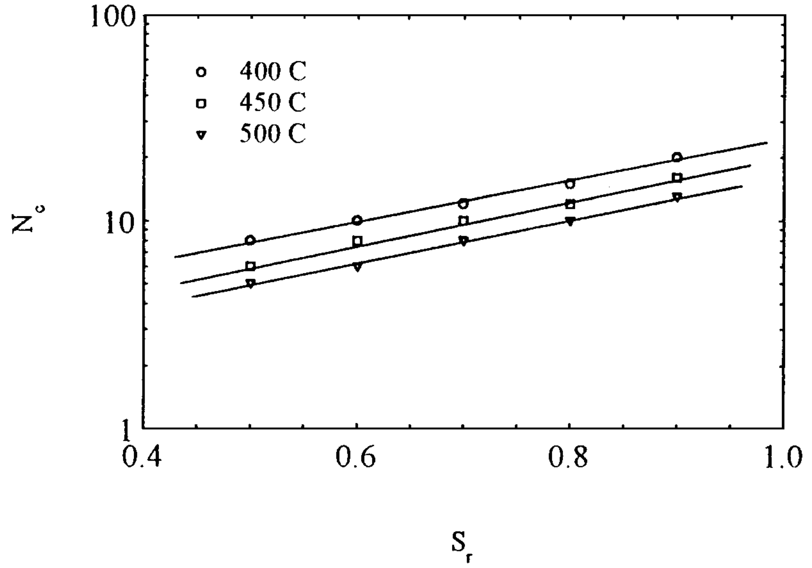


Figure 9. Inflection number of loading vs. specified relaxation stress ratio.

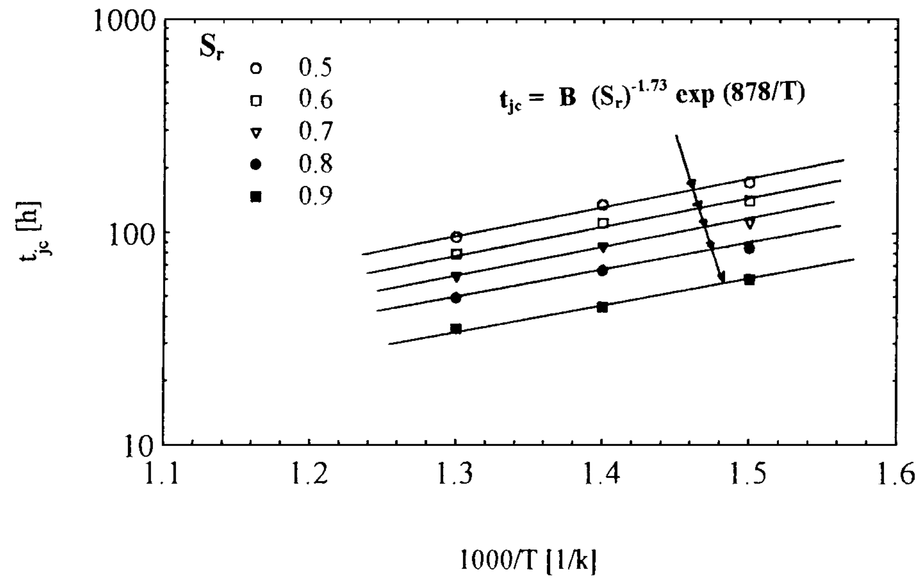


Figure 10. Inflection testing time vs. 1/T.

The stress exponent m and apparent activation energy can be determined experimentally using the following expressions

$$m = \left(\delta \ln \frac{t_{jc}}{\delta} \ln S_r\right)_{T=\text{constant}}$$

$$Q = R\left(\delta \ln \frac{t_{jc}}{\delta}(1/T)\right)_{\text{s=constant}}$$

The stress exponent m defined the slope of the S_r and t_{jc} relation (figure 8). This value is equal to 1.73 at different test temperatures.

The apparent activation energy of relaxation Q was calculated as a relation between t_{jc} and $1/T$ (figure 10). The value of Q is 7.3 Kjole/mole. The Q value does not depend on temperature value and specified relaxation stress ratio.

The material constant B for temperature 400, 450 and 500°C were 13.8, 11.0 and 9.5 respectively. Then Eq. (3) can be written in form as

$$t_{jc} = B(S_r)^{-1.73} \exp\left(\frac{878}{T}\right) \tag{4}$$

Equation 4 can be successfully utilized to predict the inflection time of this alloy throughout the temperature range.

IV. Conclusions

The stress relaxation of bolted steel 25 NiCrMo 8 has been studied in the temperature range of 400 to 500°C at different specified relaxation stress levels. The results obtained are summarized as follows:

1. On the reloading stress relaxation curves, the testing time increased as the loading number increased until certain limit of loading number and then start to decreased. This inflection point depends on the specified relaxation stress and test temperature.
2. The values of the accumulative plastic strains as a relationship of specified relaxation stress, number of loading and test temperature were observed. The empirical relation is

   $$\varepsilon_{\mathrm{p}} = 4.5 \times 10^{-4}\ (S_{\mathrm{r}})^{-2.95}\ (N)^{\mathrm{b}} \tag{1}$$

   where r is equal to $b = 0.98$, 1.07 and 1.18 at 400, 450 and 500°C respectively.
3. The stress exponent and the apparent activation energy of relaxation were calculated. The stress exponent and the activation energy are equal to 1.73 and 7.3 Kjole/mole.
4. The inflection time can be expressed satisfactorily by using the following equation

   $$t_{\mathrm{jc}} = B(S_{\mathrm{r}})^{-1.73} \exp\left(\frac{878}{T}\right) \tag{4}$$

   where T is the absolute temperature, and B is equal to 13.8, 11.0 and 9.5 at temperature 400, 450 and 500°C respectively.
5. The stress relaxation data is very important to obtain information on the permanent tightness of bolted joints, riveted assemblies, shrink fits, geskets, solderless-wrapped connections and similar devices. Stress relaxation is also of interest to designers of turbines and nuclear reactors, as in the redistribution of internal stress during reactor shutdown.

Finally, it is suggested that the technique used in this study can be generally applied to other alloys used in the mechanical elements.

Nomenclature

b	exponent
B	constant
L	length (mm)
m	stress exponent
N	number of loading
N_{c}	inflection number of loading
q	reduction in area (%)
Q	activation energy (kjole/mole)
R	gas constant (Jole/K·mol)

S_r	specified relaxation stress ratio ($\sigma_\mathrm{rj}/\sigma_\mathrm{o}$)
t	time (h)
t_j	testing time (h)
t_jc	inflection testing time (h)
T	Absolute temperature (K)
δ	elongation (%)
ε	strain (mm/mm)
ε_p	plastic strain (mm/mm)
σ	stress (MPa)
σ_0	initial stress (MPa)
σ_rj	specified relaxation stress (MPa)
σ_u	ultimate strength (MPa)
σ_y	yield strength (MPa)

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