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# ASPECTS REGARDING THE CALCULUS OF STRAINS AND EFFORTS THAT OCCUR DURING THE FIRST CYCLE IN THERMAL FATIGUE TESTS

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**Abstract**

The relations with which the axial force in the test specimen is calculated during the first stage of a thermal fatigue test derive in the paper. Useful informations for the interpretation of the results come up when comparing the values of the calculated axial force and the measured one.

## 1. Introduction

The research of the thermal fatigue phenomenon is carried out by different methods and by means of several types of installations, [1], [2].

In reference [1] a procedure is recommended which is applied on an installation of the type shown in Figure 1. Specimen, 1, with ring-shaped cross-section of the magnitude $A$, $mm^2$, is fasten by means of some grips, 2, both on the lower traverse 7 and the mobile traverse 4, which guides on columns 5. Between the mobile and the fixed traverse, 4 and 6, dynamometer 8 is assembled.

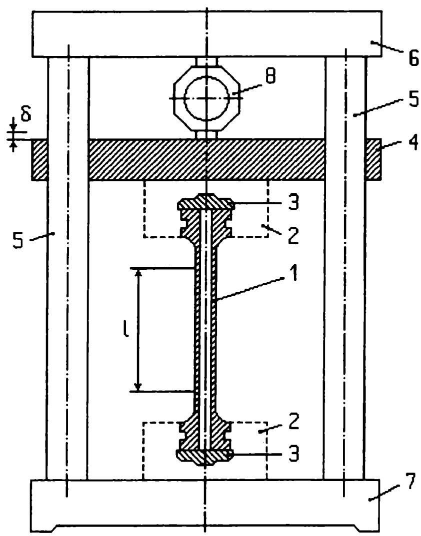

Figure 1. Installation for thermal fatigue

By means of the parts 3, the specimen is connected to an electric circuit under a voltage of 5...6 V, being run by an electric current with an intensity of 600...700 A, which heats the specimen to the desired maximum temperature of the applied thermal fatigue cycle.The specimen temperature is measured by a thermocouple (unshown) the hot welding of which is stacked on the specimen, upon its length middle. After reaching the maximum temperature, the circuit supply is cut and the specimen cools down (under the effect of an air current sent by a fan). After reaching the minimum temperature of the cycle, the electric circuit of the specimen is resumed and a new thermal cycle is applied.

During the heating stage the specimen expansion is prevented by the dynamometer in a higher or lower degree depending upon its elastic constant, $k$. A dial indicator with an accuracy of 0.001 mm (or another displacement transducer) is fastened on the fixed traverse 6 and measures the $\delta$ displacement of the mobile traverse 4.

Knowing $\delta$ value allows to determine the force developed by the dynamometer in any moment of the test:

$$N = \delta k, \tag{1}$$

where $N$ is measured in N, $\delta$ in mm and $k$ in N/mm.

The force $N$ of the dynamometer equals the axial force of the specimen, therefore the displacement $\delta$ represent, in fact, a measuring mode of both the above force and the stress from the specimen, $\sigma = N/A$.

Both thermal and mechanical cycles develop, in time, the accumulation of certain plastic deformations causing the change of both the values and even the nature of the stress acting upon the specimen and leading, at a certain point, to failure.

Depending upon the elastic constant of the dynamometer, the plastic deformations of the specimen occur after a larger or a smaller number of cycles or may even happen in the first cycle (at the end of the heating stage).

The results which will occur during the thermal fatigue test cannot be predicted in any way; they depend upon the way the materials behaves, the determination of this behaviour represents the very purpose of the experiment. From the above statement a single parameter is excepted namely the axial force developed within the specimen at the end of the heating stage in the first cycle (when, in fact, thermal fatigue phenomenon didn't even start).

In the present paper the relationships are derived based on which the maximum axial force in the specimen may be calculated in the first thermal fatigue cycle and the way is emphasised in which the comparison between the calculated and the measured values (of the above force) might help to a better interpretation of the experimental results.

## 2. Specimen deformation within the first thermal fatigue cycle

If the specimen temperature increase with $\Delta T$ grades, its free elongation reaches the value $l\alpha \Delta T$, where $l$ is the length of the specimen calibrated portion (gauge) and $\alpha$ (measured in $°C^{-1}$) is the linear thermal expansion coefficient of the material within the corresponding thermal range.

Due to the prevention of the specimen free elongation by the dynamometer, within the specimen a compression force occurs which increases with increasing temperature, reaching the maximum value at the end of the heating stage of the cycle. The maximum force value from the first cycle is designated by $N_{max}$ ; it represent the maximum value of the recorded force within the specimen, during the entire test. The moment $N_{max}$ is developed the corresponding deformation in the dynamometer becomes $\delta_{max}$ , its value being indicated by the displacement transducer. Thus, based on the measured $\delta_{max}$ value, the force is determined:

$$N_{max,m} = k\,\delta_{max}, \tag{2}$$

the designation $N_{max,m}$ being used in order to emphasise the fact that the $N_{max}$ value has been derived based on a *measured* parameter during the test.

In the following, some relationships are derived which allow to *calculate* the $N_{max}$ force, the result being designated $N_{max,c}$ . Finally, the utility of the information obtained from the condition $N_{max,m} = N_{max,c}$ is outlined.

The moment $N_{max}$ is reached, the specimen undergoes the compression deformation $\Delta l_{max}$ . The relationship between the absolute displacements values is:

$$l\alpha\,\Delta T = \delta_{max} + \Delta l_{max} \tag{3}$$

Depending upon the both the elastic constant of the dynamometer and the mechanical and elastic characteristics of the specimen material, it is possible that $\Delta l$ elongation to be either entirely elastic (Figure 2.a) or to have an elastic ($\Delta l_e$ ) and a plastic ($\Delta l_p$ ) component (Figure 2.b).

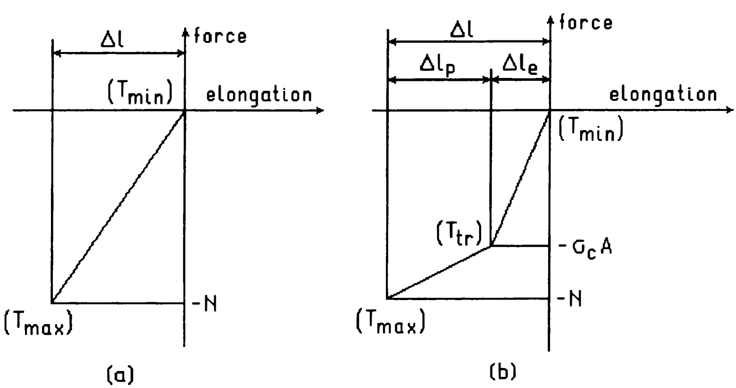


Figure 2 Diagrams force - elongation

The diagrams illustrated in Figure 2 are similar to the characteristic curve of the specimen. As already known, within the elastic domain the characteristic curve is linear and elasticity modulus of the material is constant while within the plastic domain the curve is non-linear but they be approximated with a straight line which has a constant "equivalent elasticity modulus".

It is however noticeable that the diagrams shown in Figure 2 are not actually characteristic curves since temperature isn't maintained constant during the test and elasticity modulus varies with temperature.

The linear representation assume some average values for the elasticity moduli, as follows:

- for figure 2a: $E_e$ - average of the values of elasticity modulus, within the elastic domain, corresponding to the temperatures $T_{min}$ and $T_{max}$;
- for figure 2b: $E_e$ - average of the values of elasticity modulus, within the elastic domain, corresponding to the minimum temperature $T_{min}$ and to the passing temperature $T_{tr}$ from elastic to the plastic domain; $E_p$ - average of the values of equivalent elasticity modulus, within the plastic domain, at the temperatures $T_{tr}$ and $T_{max}$.

It is important to specify that, at the temperature $T_{tr}$, the stress within the specimen equals the yield strength, $\sigma_c$, which will be subsequently replaced by the conventional $R_{p\,0,2}$ yield limit for which the corresponding force is $A \cdot R_{p\,0,2}$.

In case the specimen is tested only in the elastic domain, the deformation is calculated with an already-known relationship, from the resistance of materials:

$$\Delta l_{\max} = \Delta l_e = \frac{Nl}{E_e A}, \tag{4}$$

and in case the specimen is deformed both elastically and plastically $\Delta l_{max} = \Delta l_e + + \Delta l_p$, that is

$$\Delta l_{\max} = \frac{R_{p\,0,2} A l}{E_e A} + \frac{(N_{\max} - R_{p\,0,2} A) l}{E_p A}. \tag{5}$$

By replacing (1) and (3), or (1) and (4) into (2) the corresponding relationship for the calculation of maximum axial force are derived:

- in the case where only elastic deformations:

$$N_{\max,c} = \frac{l \alpha \, \Delta T}{\dfrac{l}{E_e A} + \dfrac{1}{k}}; \tag{6}$$

- in the case where both elastic and plastic deformations:

$$N_{\max,c} = \frac{l\alpha\,\Delta T + R_{p0,2}\,l(\frac{1}{E_p} - \frac{1}{E_e})}{\frac{l}{E_p A} + \frac{1}{k}} \tag{7}$$

### 3. Utilisation mode of the derived relationship and conclusions

During the thermal fatigue test, the cyclic variation of δ displacement, is recorded which serves to analyse, on one hand, the way the limits of this displacement are modified as a function of the number of applied cycles and, on the other hand, the way the displacement vary within certain cycles. Based on these analyses the accumulation of plastic deformation with time is estimated in order to settle a connection between this accumulation and number of cycles until failure.

For these data processing the following values must be known:

a) the specimen cross-section area, $A$, and the dynamometer elastic constant, $k$ ;
b) the physical and mechanical characteristics of specimen material: α, $E_e$ ,$E_p$ ,$R_{p\,0,2}$ ;
c) the specimen length, $l$ and the temperature variation, $\Delta T$ .

These values have been grouped in the above mode, according to their accuracy: the values of the parameters included at (a) are exactly known; those of the (b) category may be exactly enough determined, while the values of (c) parameter cannot be settled by direct measurements. During the thermal fatigue tests, performed according to the method detailed within the present paper, no sharply limited zone of $l$ length could be observed upon which the temperature varies with $\Delta T$ as compared to the rest of the specimen. Consequently, the product value $l\alpha\,\Delta T$, representing the free expansion of the specimen and constituting an essential parameter for analysing the test results, cannot be specified. The value of this elongation is also influenced by the strains which occur in certain portions of the specimen, outside in calibrated zone. These portions are subjected to other temperature variations, different from $\Delta T$ . It follows that the values $l$ and $\Delta T$ cannot be determined by direct measurements on the specimen but only by indirect methods, one of them being introduced in this paper.

The fact that the axial force $N_{max}$ may be obtained by means of two procedures, one based on direct measurement and other based on calculation, using the equations (6) and (7), leads to two kinds of restrictive conditions.

The first is under the form:

$$\frac{l\alpha\,\Delta T}{\frac{l}{E_e A} + \frac{1}{k}} - k\delta_{\max} = 0 \quad , \tag{8}$$

which is derived from (2) and (6) being true for the case when only elastic deformations occur within the first cycle.

The later is under the form:

$$N_{\max,c} = \frac{l\alpha\,\Delta T + R_{p0,2}\, l(\frac{1}{E_p} - \frac{1}{E_e})}{\dfrac{l}{E_p A} + \dfrac{1}{k}} \tag{9}$$

which results from (2) and (7) providing in the first cycle both elastic and plastic deformations are noticed.

For a set of thermal fatigue tests, performed on same material, between the same temperature limits, using specimens with the same lengths but with different cross-sections and employing dynamometers with different elastic constants, on the tensile testing machine, several conditions of the form (8) or (9) are obtained. These conditions allow, on one hand, to estimate whether or not the values $E_e$ , $E_p$ have been correctly-adopted and, on the other hand, to settle certain equivalent values for both the specimen length $l$ and for the temperature variation $\Delta T$.

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