The specific heat loss combined with the thermoelastic effect for an experimental analysis of the mean stress influence on axial fatigue of stainless steel plain specimens

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ABSTRACT. The energy dissipated to the surroundings as heat in a unit volume of material per cycle, \( Q \), was recently proposed by the authors as fatigue damage index and it was successfully applied to correlate fatigue data obtained by carrying out fully reversed stress- and strain-controlled fatigue tests on AISI 304L stainless steel plain and notched specimens. The use of the \( Q \) parameter to analyse the experimental results led to the definition of a scatter band having constant slope from the low- to the high-cycle fatigue regime. In this paper the energy approach is extended to analyse the influence of mean stress on the axial fatigue behaviour of un-notched cold drawn AISI 304L stainless steel bars. In view of this, stress controlled fatigue tests on plain specimens at different load ratios \( R \) (\( R=-1; R=0.1; R=0.5 \)) were carried out. A new energy parameter is defined to account for the mean stress effect, which combines the specific heat loss \( Q \) and the relative temperature variation due to the thermoelastic effect corresponding to the achievement of the maximum stress level of the stress cycle. The new two-parameter approach was able to rationalise the mean stress effect observed experimentally. It is worth noting that the results found in the present contribution are meant to be specific for the material and testing condition investigated here.

KEYWORDS. Dissipated energy density; Mean stress effect; Fatigue; Thermoelastic temperature; Fatigue life estimation; Thermometric methods.

INTRODUCTION

The fatigue damage monitoring and the fatigue life assessment of materials and components can be experimentally performed by using the surface temperature. In fact for a given set of boundary conditions (i.e. load test frequency, room temperature, specimen geometry), the temperature of a material undergoing fatigue increases as the applied stress amplitude increases. Stoymeyer [1] adopted the dissipated energy to evaluate the fatigue limit of plain steel specimens; in particular he measured the temperature increase of a steady stream of water covering the specimen. More recently, Curti et al. proposed the “limit temperature” [2] and later La Rosa and Risitano suggested an experimental procedure for the rapid determination of the material fatigue limit [3], based on the temperature measurement by using an infrared camera. Recently Risitano et al. proposed a fatigue life assessment method valid for variable amplitude fatigue [4] and a thermographic method to evaluate the material fatigue limit by means of a static tensile test [5]. Curà et al. developed a methodology for the rapid determination of the material fatigue limit, based on an iterative method to
recognise the temperature measurements obtained from specimens loaded by stress amplitude higher or lower than the fatigue limit [6]. Giancane et al. analysed the non-uniform temperature distribution in the case of aluminium alloys [7]. In ref. [8] an experimental procedure was proposed to evaluate the energy dissipated as heat in a unit volume of material per cycle, \( Q \), starting from temperature measurements. The \( Q \) parameter was then adopted as a new experimental damage index useful for fatigue life estimations. Recently, the use of the \( Q \) parameter enabled us to rationalise several experimental results generated from constant amplitude, push-pull, stress- or strain-controlled fatigue tests on plain and notched hot rolled AISI 304 L stainless steel specimens [9, 10] as well as from cold drawn un-notched bars of the same steel under fully-reversed axial and torsional fatigue loadings [11]. Here we recall that notched specimens had either lateral U- or V- notches, with root radii equal to 3 or 5 mm, or a central hole with radius equal to 8 mm. Fig. 1 shows the axial and the torsional fatigue test results in terms of net-section stress amplitude \( \sigma_{an} \) or \( \tau_{an} \), respectively, the mean fatigue curves and the 10%-90% scatter bands. The figure reports also the inverse slope \( k \) of the curves, the stress-based scatter index \( T_{\sigma}=\sigma_{10\%}/\sigma_{90\%} \) (T\(_{\sigma}\)) and the life-based scatter index \( T_{N,\sigma} \) (T\(_{N,\sigma}\)). In the case of strain-controlled fatigue tests, the stress amplitude reported in Fig. 1 is the value measured at half the fatigue life. Fig. 2 shows the same fatigue data re-analysed in terms of the \( Q \) parameter. In particular, the 10%-90% scatter band shown in the figure was fitted only on the fatigue data published in [10]. However, Fig. 2 shows that fatigue data obtained under axial and torsional fatigue tests [11] can be interpreted by the same scatter band. More than 120 fatigue data are included in the figure.

\[
Q \cdot f = -\rho \cdot c \cdot \frac{\partial T}{\partial t}
\]  

(1)

where

\( f \) is the load test frequency,

\( T \) is temperature,

\( t \) is time,

\( \rho \) is the material density

\( c \) is the material specific heat.

Concerning the stainless steel material analysed in the present paper, the material density \( \rho \) and the specific heat \( c \) were experimentally measured and resulted 7940 kg/m\(^3\) and 507 J/(kg K), respectively [12]. According to Eq. (1), it is possible to evaluate the thermal power \( (Q \cdot f) \) dissipated in steady state conditions by measuring the cooling gradient just after the
test interruption. Eq. (1) enables one to measure readily and in-situ the specific heat loss $Q$ at any point of a specimen or a component undergoing fatigue loadings.

Figure 2: Fatigue data shown in Fig. 1 analysed in terms of energy released as heat by a unit volume of material per cycle. Scatter bands are defined for 10 and 90% survival probabilities.

Recently, the energy-based approach has been extended in order to take into account the presence of non-zero mean stresses [13]. In literature sound stress/strain-based approaches are available that include the influence of mean stresses; a common feature of them is to combine different mechanical parameters. Smith, Watson and Topper [14] proposed the SWT parameter to extend the Manson-Coffin approach:

$$SWT = \sqrt{\frac{\sigma_{\text{max}} \cdot E \cdot \varepsilon}{\text{max}}}$$

where

- $\varepsilon_a$ is the applied strain amplitude,
- $E$ the material elastic modulus,
- $\sigma_{\text{max}}$ the maximum stress.

Among the fracture mechanics-based approaches, Walker [15] and more recently Vasudevan et al. [16], Kujawsky [17, 18] and Stoychev and Kujawsky [19] proposed the parameter:

$$\Delta K_{\text{eq}} = \Delta K^{(1-a)} \cdot K_{\text{max}}^a$$

(3)

to rationalise fatigue crack growth rate data, characterised by different values of the mean stress. In Eq. (3), $\Delta K$ and $K_{\text{max}}$ are the range and the maximum value of the stress intensity factor, respectively, and $\alpha$ is a best fitting parameter to determine from the experimental data.

Eq. (2) and (3) show that the driving force of the crack nucleation, Eq. (2), and propagation, Eq. (3), is characterised by two parameters: the amplitude (or range) of the driving force and its level (i.e. its maximum value). Both the parameters involved in Eq. (2) and Eq. (3) were interpreted by the authors of this paper in terms of energy, i.e. the hypothesis was formed that the fatigue strength depends on a thermodynamic exchange variable as well as on a state variable. After that, the $Q$ parameter was identified as the exchange variable, whereas the thermoelastic temperature $T_{\text{the}}$ was assumed as the state variable. The thermoelastic temperature $T_{\text{the}}$ is the temperature that would be achieved by the material when loaded at the maximum stress level of the fatigue cycle, $\sigma_{\text{max}}$, in an adiabatic process. $T_{\text{the}}$ can be evaluated analytically or experimentally by loading the material in its elastic field and then by extending the temperature-applied stress relation up to the $\sigma_{\text{max}}$ value. The applied stress rate must be properly set in order to reduce the heat transfer between material and the surroundings, i.e. to make the loading process adiabatic. As it will be discussed in a dedicated section, it was found that such nearly adiabatic conditions can be reached in standard laboratory tests, at least for the material analysed in this paper.
Alternatively, the thermoelastic temperature $T_{th}$ can be easily calculated from Eq. 4, which relates $T_{th}$ to the maximum applied stress [20]:

$$T_{th} = \left( \frac{\alpha}{\rho \cdot c} \right) \sigma_{max} = -K_m \cdot \sigma_{max}$$

(4)

where $T_0$ is the material temperature when the applied stress is equal to zero and $\alpha$ the material thermal expansion coefficient. Therefore the new equation proposed in the present paper to rationalise the mean stress influence on axial fatigue of stainless steel plain specimens is:

$$Q \cdot \left( \frac{T_{th}}{T_0} \right)^b \cdot N_f = (\overline{N})^m \cdot N_f = \text{cost}$$

(5)

where $b$ and $m$ are material constants to evaluate by fitting the experimental data.

**MATERIAL, SPECIMENS’ GEOMETRY AND TEST PROCEDURE**

The material selected for the experimental tests consisted of 25-mm-diameter AISI 304 L cold drawn bars, having an engineering tensile strength, $R_{m02}$, and an engineering proof stress, $R_{p02}$, equal to 691 MPa and 468 MPa, respectively. The material adopted in this work is different from that analysed in [10], characterised by $R_{m}=700$ MPa and $R_{p02} = 315$ MPa. As to the material analysed in the present paper, the mechanical properties, the chemical composition, the Vickers hardness and the average grain size are listed in Tab. 1 [11].

| E [MPa] | $R_{p02}$ [MPa] | $R_m$ [MPa] | A [%] | HV30 | C [%] | Si [%] | Mn [%] | Cr [%] | Mo [%] | Ni [%] | Cu [%] | Average grain size* [μm] |
|---------|----------------|-------------|-------|------|-------|--------|--------|--------|--------|--------|--------|----------------|----------------------|
| 192200  | 468            | 691         | 43    | 199  | 0.013 | 0.58   | 1.81   | 18.00  | 0.44   | 8.00   | 0.55   | 35     |

Table 1: AISI 304 L material properties (*According to ASTM E 112 [21]).

Constant amplitude, stress-controlled fatigue tests were carried out on a servo-hydraulic MFL machines equipped with a 250 kN load cell and a MTS Testar IIm digital controller. Three different load ratios $R$ ($R=-1$, $R=0.1$ and $R=0.5$) were adopted. In the case of load ratio equal to $R=-1$ and $R=0.1$, the specimens’ geometry is shown in Fig. 3a, whereas that adopted for $R=0.5$ is reported in Fig. 3b. The load test frequency was selected in the range 1-30 Hz and as high as possible in order to maintain the stabilised temperature of the material below 70°C during the whole fatigue test. Then the fatigue test was suddenly stopped to measure the cooling gradient and to evaluate the Q parameter, according to the experimental procedure proposed in [8]. The fatigue tests were run until the specimen’s failure or to 2 million cycles (run-out specimen).

![Figure 3: Specimens’ geometry adopted for fatigue tests having a) load ratio $R=-1$ e $R=0.1$ and b) $R=0.5$.](image)

To evaluate the thermoelastic material constant $K_m$, Eq. (4), load controlled ramps were executed at different load rates by means of a servo-hydraulic Sehenck Hydropuls PSA 100 machine equipped with a 100 kN load cell and a Trio Sistemi RT3 digital controller.

During all tests, the specimen’s temperature was measured by using a copper-constantan thermocouple having diameter of 0.127 mm, which was fixed at the specimen’s centre by means of a silver-loaded conductive epoxy glue. Temperature
signals generated by the thermocouples were acquired by means of a data logger Agilent Technologies HP 34970A operating at a maximum sample frequency, $f_{\text{ samp }}$ of 22 Hz (accuracy equal to 0.02 °C).

**Fatigue test results**

Fig. 4 shows the fatigue test results and reports the mean curves in terms of the engineering stress amplitude $\sigma_a$, the 10%-90% survival probability scatter bands, the inverse slope $k$, the reference fatigue strength $\sigma_{A,50\%}$ evaluated at $N_A=2$ million cycles with a survival probability equal to 50%, and the stress- as well as the life-based scatter index $T_\sigma$ and $T_{N_A}$, respectively. The experimental data were statistically re-analyzed under the hypothesis of log-normal distribution of the number of cycles to failure with a 95% confidence level. It can be seen that the fatigue behaviour of the analysed material is significantly affected by the load ratio: in fact $\sigma_{A,50\%}$ evaluated under push-pull fatigue test ($R=-1$) is reduced of a factor equal to 1.27 and 1.86, in the case of $R=0.1$ and $R=0.5$, respectively.

It is worth noting that in all fatigue tests carried out by imposing a load ratio equal to $R=0.5$ and in many tests conducted at $R=0.1$, the maximum stress was higher than the material proof stress. Therefore, the cyclic material stabilisation was monitored by considering the axial displacement measured by the displacement transducer of the test machine. After stabilisation, the reduction of the specimen diameter ranged from 4.5% to 19.5% with respect to the initial diameter, depending on the applied stress amplitude.

![Figure 4: Fatigue data analysed in terms of engineering stress amplitude for different load ratios. Scatter bands are defined for 10% and 90% survival probabilities.](image)

**Energy-based fatigue test results**

In order to evaluate the evolution of $Q$ parameter, each fatigue test was interrupted several times. Fig. 5 shows some characteristic examples of $Q$ values plotted against the number of cycles normalised with respect to the number of cycles to failure or, in the case of run-out specimens, with respect to 2 millions. One can observe that the $Q$ values span in a range between 0.01 and 5 MJ/(m³·cycle) by considering the different load ratio analysed in this paper, in spite of a variation of $\sigma_a$ from 155 to 400 MPa. According to [8], the fatigue test results were re-analysed in terms of the characteristic value of $Q$ measured at 50% of the number of cycles to failure or, in the case of run-out specimens, at 1 million cycles. Fig. 6 shows the results of the statistical analysis in the hypothesis of log-normal distribution of the number of cycles to failure $N_t$ and constant scatter with respect to the energy dissipation level. The mean and the 10% - 90% survival probability curves fitting the experimental results with a confidence level of 95% have the following expression:

$$Q^* \cdot N_j = \cos t$$  \hspace{1cm} (6)

The figure reports the inverse slope $k$ of the curves, the mean energy value $Q_{A,50\%}$ at the reference fatigue life $N_A$ of two million cycles and the energy- as well as the life-based scatter index $T_{Q}$ and $T_{N_A,Q}$, respectively. Fig. 6 shows that the data...
obtained by carrying out fatigue tests at different load ratios cannot be rationalised in a single scatter band by using the Q parameter.

![Figure 5: Measured Q trends against the number of cycles normalised with respect to the number of cycles to failure, Nf.](image)

**Figure 5:** Measured Q trends against the number of cycles normalised with respect to the number of cycles to failure, Nf.

<table>
<thead>
<tr>
<th>R</th>
<th>k</th>
<th>QA,50% [MJ/(m³·cycle)]</th>
<th>TQ</th>
<th>TN,Q [cycles]</th>
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<td>2.99</td>
<td>8.75</td>
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</tbody>
</table>

**Figure 6: Fatigue data analysed in terms of energy released as heat by a unit volume of material per cycle. Scatter bands are defined for 10 and 90% survival probabilities.**

**Experimental Evaluation of the Thermoelastic Constant**

To experimentally evaluate the thermoelastic constant $K_m$ (see Eq. 4), load-controlled ramps at different load rates were carried out, aiming at the evaluation of the minimum stress-rate $\dot{\sigma}$ required to achieve adiabatic test conditions. Five stress rates were applied, namely $\dot{\sigma} = 5, 19, 37, 54$ and 73 MPa/s. The tests were conducted by applying an initial compressive stress equal to $-150$ MPa, followed by a ramp up to 150 MPa. The value of 150 MPa was chosen to guarantee the linear elastic behaviour of the analysed material. The adopted procedure can be summarised as follows:

- application of a compressive stress equal to $-150$ MPa applied to the specimen;
- holding of the compressive stress to allow for material thermal equilibrium with the surroundings (reference temperature $T_0$);
- execution of a tensile ramp up to 150 MPa with given $\dot{\sigma}$ value and measurement of the corresponding temperature drop. Since $T_0$ is the reference temperature at a stress of $-150$ MPa, the thermoelastic temperature $T_{the}$ reached at the end of the test will be referred to a stress of 300 MPa.

Fig. 7 shows as an example the results of a test conducted at $\dot{\sigma} = 54$ MPa/s. Within the time window $(t_i-t_f)$, it can be observed that the temperature decreases from the initial value $T_0 = 301.25$ K. The stress range adopted to evaluate $K_m$ corresponds to the stress variation in the time window $\Delta t = t_i-t_f$ ($\Delta \sigma = \sigma(t_f) - \sigma(t_i)$), that is 297 MPa in Fig. 7.
The $K_m$ values measured in all static tests are collected in Fig. 8. It can be observed that by increasing the applied stress rate, the scatter of the $K_m$ values decreases and that a 5.4% variation of the $K_m$ mean value was noticed (from $3.86 \cdot 10^{-12}$ to $3.65 \cdot 10^{-12}$ Pa$^{-1}$), by increasing the stress rate of a factor about 2 (from 37 to 73 MPa/s). Therefore from an engineering point of view, it can be concluded that adiabatic conditions can be reached by imposing a stress rate higher than 37 MPa/s, at least for the material and test conditions analysed in this paper. The final $K_m$ value adopted was equal to $3.75 \cdot 10^{-12}$ Pa$^{-1}$, being the mean value measured for $\dot{\sigma} = 37$, 54 e 73 MPa/s; it is in good agreement with the theoretical value of $3.97 \cdot 10^{-12}$ Pa$^{-1}$ that can be calculated by using Eq. (4) and assuming $\alpha = 16 \cdot 10^{-6}$ K$^{-1}$.

**THE NEW TWO-PARAMETER, ENERGY-BASED APPROACH APPLIED TO THE EXPERIMENTAL RESULTS**

After evaluating the thermoelastic constant $K_m$, the thermoelastic temperature relevant to each specimen was calculated according to Eq. (4). Having in hands $Q_0$, $\left[\frac{T_{in}}{T_0}\right]$, and the number of cycles to failure $N_f$ for each coupon, the parameters $b$ and $m$ of Eq. (5) were calculated. In more detail, the experimental results were plotted in a $Q_0$-$\left[\frac{T_{in}}{T_0}\right]$ plane, for a given number of cycles to failure, as shown in Fig. 9. By considering the available number of data and independently of the load ratio $R$, the fatigue results were divided in 4 groups, characterized by a different range of the number of cycles to failure ($N_f \leq 10000$ cycles; $20000 \leq N_f \leq 60000$ cycles; $80000 \leq N_f \leq 120000$ cycles e $N_f \leq 300000$ cycles).
Dashed regression lines in Fig. 9 (a log-log diagram) were calculated for each group. By considering the reduced variation among the $h$ values from an engineering point of view, a unique $h$ value was calculated and resulted equal to 4.57 (continuous line in Fig. 9).

After that, all available data were plotted in a $Q$-$N_f$ plane (see Eq. 5, $h=4.57$) and re-analyzed as a single population, independently of the load ratio, under the hypothesis of log-normal distribution of the number of cycles to failure and with a 95% confidence level. The result is shown in Fig. 10, where the mean line, the 10% - 90% survival probability curves, the inverse slope $m$, the equivalent energy $T_Q$ and the life-scatter $T_N$ indexes are plotted.

By considering the stress amplitude as well as the dissipated energy-based curves (plotted in Fig. 4 and Fig. 6, respectively), one can appreciate that the new $Q$ parameter collapses all the fatigue data into a single scatter band having a constant slope from $10^3$ to $2\cdot10^6$ cycles, despite the different load ratios involved. Moreover, it is worth noting that the scatter index $T_N$ in Fig. 10 is very close to that relevant to the “$R=-1$” and “$R=0.1$” series presented in terms of stress amplitude (see Fig. 4) as well as to the “$R=-1$” series expressed in terms of $Q$ parameter (see Fig. 6).
CONCLUSIONS

In this paper a two parameter, energy-based approach has been presented to rationalise the influence of the load ratio on the fatigue behaviour of AISI 304 L cold drawn steel bars. Three different load ratios (namely R=-1, R=0.1 and R=0.5) were applied in the constant amplitude fatigue tests. The mean stress influence was considered by combing the specific heat loss with the thermoelastic temperature relevant to the maximum stress of the load cycle. The new two-parameter, energy-based method enabled us to collapse all fatigue test results in a single scatter band having a constant slope from $10^3$ to $2\cdot10^6$ cycles. The scatter index resulted equal to that of single test series expressed in terms of stress amplitude. Static tests at different stress rate were carried out to experimentally measure the thermoelastic constant of the material, which is needed to calculate the thermoelastic temperature. It was observed that adiabatic test conditions required to measure the thermoelastic constant can be achieved by using a standard laboratory environment. This new approach has not been tested yet against materials different from that analysed in the present paper.

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