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COMPARISON OF ANALYSIS METHODS OF DATA FROM THERMOGRAPHIC MEASUREMENTS OF AL 2024 FATIGUE LIMIT FOR R=0.1

POROVNÁNÍ METOD PRO ANALÝZU DAT Z TERMOGRAFICKÝCH MĚŘENÍ MEZE ÚNAVY MATERIÁLU AL 2024 PRO R=0,1

Abstract

The traditional methods for fatigue characterization of metallic materials are expensive and extremely time consuming. In order to overcome these shortcomings, the Thermographic Method (TM), based on thermographic analysis, is applied to estimate the fatigue limit of Al 2024. The temperature increase due to localized microplasticity is considered as the fatigue damage indicator. An experimental program is carried out to assess the fatigue limit both as resulting from the *S*–*N* field and, directly, from thermographic measurement. For the latter, three different methods are applied for the estimation of the AL 2024 fatigue limit and the out-coming results discussed. The values of fatigue limit predicted from the thermographic method according to the three methods are in good agreement to that derived from the traditional *S-N* procedure.

Abstrakt

Stanovení meze únavy kovových materiálů tradičními metodami je ekonomicky a časově velmi náročné. Za účelem snížení časové a finanční zátěže je provedeno srovnání termografické metody (TM) při stanovení cyklické meze únavy hliníkové slitiny AL 2024. V důsledku lokalizace mikroplasticity se zvýší teplota, kterou lze považovat za indikátor vzniku trvalého únavového poškození. Experimenty jsou provedeny ve dvou rovinách. Tradiční cestou jsou změřeny *S-N* křivky a souběžně jsou provedena termografická měření na materiálu AL 2024. Pro zpracování naměřených dat z TM jsou využity tři dostupné vyhodnocovací metody, známé z literatury. Je hodnocena/diskutována přesnost odhadu/určení meze únavy AL 2024 z jednotlivých metod. Odhad/určení meze únavy z tradičních metod a za použití termografické metody vykazují shodné výsledky.

Keywords

Thermographic method, Wöhler curve, Risitano et al. method, Canteli et al. method, fatigue limit, Al2024.

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1 INTRODUCTION

The application of infrared thermography as a non-destructive method to detect the occurrence of damage and to investigate the fatigue process of materials has become extensive and is widely investigated in the literature in the last twenty years [1-7]. From the experimental point of view, thermographic techniques allow us to measure the surface temperature of a specimen by means of an infrared thermal scanner and to monitor its increase during the test.

On the basis of thermal experimental data, different methods of analysis have been developed over the last years in order to correlate the temperature growth to the physical damage process and failure of materials [1,2,4]. The experimental curves reporting the surface temperature in specimens versus the number of cycles have shown three characteristic phases as pointed out in [6]. As a consequence, they proposed that the fatigue limit could be determined by plotting the stabilisation temperature (already quoted in [6]) or the initial temperature slope against the applied stress and finding the value of the fatigue limit as the intercept of the curve on the stresses axis (nil temperature increasing or nil initial temperature slope). These results have been verified and analyzed in [3,6] by La Rosa and Risitano. The thermographic method has been successfully applied to different materials (steels [3] and aluminium alloys [5], etc.) under different configurations (notched specimens, butt welded joints). In [3,6] some indications for both the correct application of the experimental thermographic method and the correct data processing have been given. In [6] the fatigue limit is derived primarily as stress range and then compared with that resulting from the Risitano methodology. With the purpose of improving the estimation of the fatigue limit, a novel assessment procedure of the thermographic results is presented allowing an improved correspondence between the fatigue limits arising from both models to be achieved, thus confirming the suitability of the thermographic technique in practical applications.

In the present work thermographic methods, as proposed by Risitano et al. [6], Canteli et al. [3] and Seitl et al. [7], are applied to the material Al 2024 with the aim of evaluating in very short time the fatigue limit for a stress ratio R = 0.1 for the above mentioned methods, comparing their value and discussing their suitability (in the sense of advantage or disadvantage). The thermographic values of the fatigue limit are compared with that obtained applying the traditional procedure represented by the S-N curve.

2 MATERIALS AND METHODS

2.1 Al 2024

The material tested in the present research is Al 2024, widely used in mechanical components of aircrafts, the chemical composition of which is given in Table 1, while the mechanical properties, according to the static tensile tests, are presented in Table 2. The dimensions of the specimens are shown in Fig. 1. The tested specimens were made from the Al 2024 sheet with the length direction parallel to the rolling direction. All the specimens were painted black in order to reduce the infrared reflections and improve the surface heat radiation.

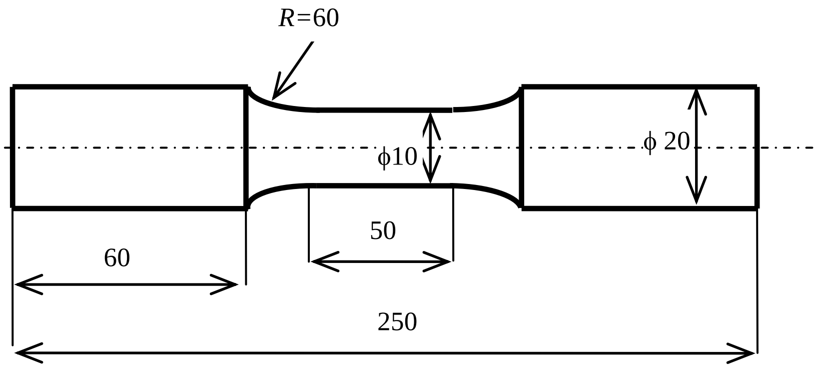

Fig. 1 Dimensions of specimens

Tab. 1 Chemical compositions of Al 2024 in wt %.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others	Al
0.50	0.50	3.8-4.9	0.3-0.9	1.2-1.8	0.1	0.25	0.15	0.15	rest

Tab. 2 Mechanical properties of Al 2024

Tensile Strength [MPa]	Yield Strength [MPa]	Elongation prior to fracture %	Poisson's ratio ν [-]	Elastic modulus E [MPa]
462	400	5	0.34	0.72×10^5

2.2 Experimental investigation

Fatigue tests were carried out at normal room temperature about 25ºC.

a) The traditional fatigue measurement

An AMSLER pulsator with 20 kN load capacity was used for testing. The frequency, between f = 30 a 45 Hz, was determined in accordance to the rigidity of the whole experimental set up. A load controlled mode for stress ratio R = 0.1 was used. Constant amplitude tests were conducted at maximum stress amplitude ranging from 80 to 160 MPa, in order to determine the traditional fatigue S-N curve and amplitude fatigue limit σ_{afSN}.

b) Thermographic fatigue measurement

A fully computerized servo-hydraulic 100 kN MTS dynamic machine was used in a stepwise succession of increasing fatigue load allowing the lock-in infrared thermography to be applied for rapid determination of the amplitude fatigue limit σ_{afTM}. The stress amplitude started at 110 MPa with 10 MPa steps until the occurrence of the final fracture. During the fatigue tests, the A320G Flir camera was used to visibly record the thermographic images in real time. The temperature sensitivity of the camera is less than 0.025°C.

3 RESULTS AND DISCUSSION

3.1 The traditional fatigue results

Fig. 2 presents the fatigue S-N curve in log-log scale by fitting the traditional fatigue data using the least-square method. The logarithm of the fatigue life $\log(N_f)$ was assumed to be the dependent variable in the linearized S-N curve, whereas the logarithm of the stress amplitude $\log(\sigma_a)$

was considered to be the reference variable. In the present fatigue tests, the fatigue limit for a limit number of cycles of 10^7 cycles is found to be $\sigma_{afSN} \cong 100$ MPa. This value is accepted as the "true" or reference value of the fatigue limit, according to the philosophy of the EN-3 Fatigue [8].

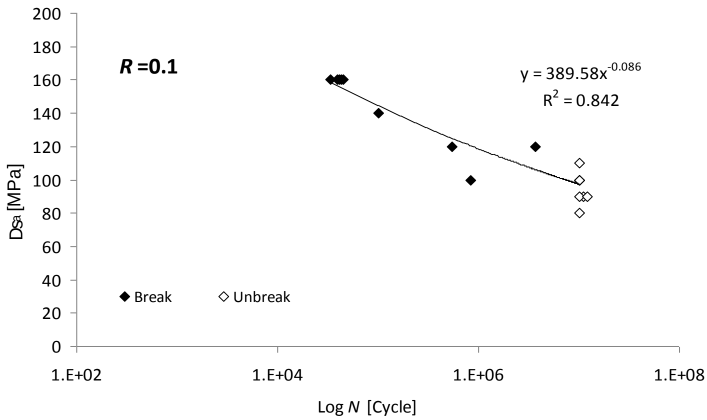

Fig. 2 The traditional fatigue *S-N* curve for AL 2024

3.2 The infrared thermographic results

To determine the fatigue limit of a material or a component by the infrared thermography, it is important to obtain the asymptotic temperature increment ΔT or the initial temperature gradient $\Delta T/\Delta N$ on the specimen surface by means of an infrared camera. Fig. 3 presents the temperature variations of a cylindrical specimen. The hot-spot zones on the specimen surface are visibly identified through the thermal images obtained by the infrared camera. From Fig. 3, the temperature in the gage length of the specimen is obviously observed to increase, indicating that the plastic deformation is occurring throughout the gage-length section. It is apparently observed that the hot-spot zone expanded during the fatigue tests, demonstrating a strongly localized fatigue damage phenomenon.

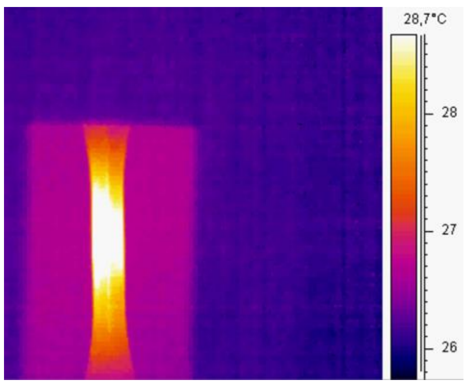

Fig. 3 Infrared thermal detection of Al 2024 during the fatigue test using an A320G Flir camera

The measured temperature increments measured on the specimen as a result of the successive loading steps were readily registered by using the infrared thermography technique as a function of the applied cyclic stress amplitudes, which are higher than the fatigue limit of Al 2024. Based on the couples (ΔT ; $\Delta\sigma_a$), according to Risitano et al. [6], a regression line is plotted applying the least square method, leading to a fatigue limit σ_{afTM} of 99.97 MPa by extrapolating the straight line down to zero at the $\Delta\sigma_a$ – axis, as shown in Fig. 4.

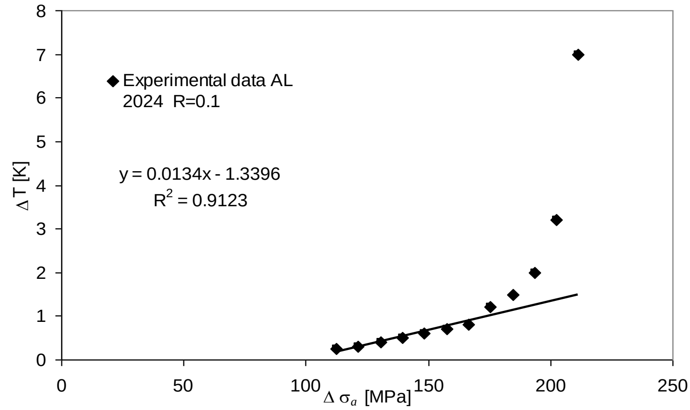

Fig. 4 Fatigue limit determination using the infrared thermography – method by Risitano et al. [6]

The second method, also suggested by Risitano et al. [6], uses the initial temperature gradient $\Delta T/\Delta N$. Based on the couples ($\Delta T/\Delta N$; $\Delta\sigma_a$), a regression line is plotted by applying the least –square method from which a fatigue limit σ_{afTM} = 95.00 is obtained by extrapolating the straight line down to zero at the $\Delta\sigma_a$ – axis, as presented in Fig. 5.

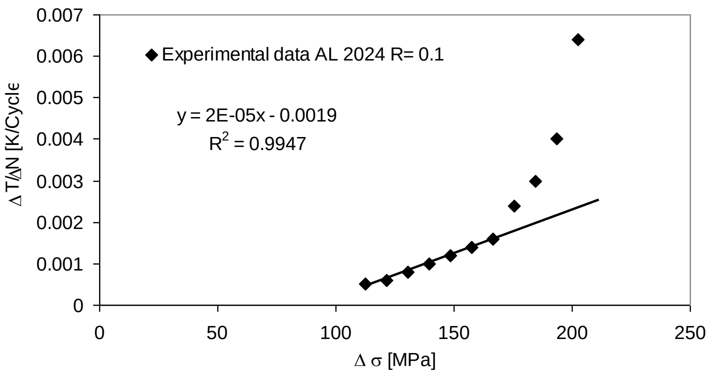

Fig. 5 Fatigue limit determination using the infrared thermography – second method by Risitano et al. [6]

As an alternative, Canteli et al. [4] postulated that the evolution of the temperature range may be better represented by a continuous function $\Delta T = \Delta T(\Delta\sigma_a)$ at a logarithmic scale, implying the following procedure.

First, a normalized stress range is achieved by

$$\Delta\sigma_a^{\ *} = \frac{\Delta\sigma_a - \Delta\sigma_{a0}}{\Delta\sigma_{aup} - \Delta\sigma_{a0}} \ , \tag{1}$$

where

$\Delta\sigma_{a0}$ – the fatigue limit for $N \to \infty$,

$\Delta\sigma_{aup}$ – an upper limit of the stress range where, theoretically, the thermal emission grows without limit.

Because the normalized variable $\Delta\sigma_a^*$ is a monotonically increasing function of ΔT and its range is the interval (0; 1), can be represented by a cumulative distribution function. Assuming a Gumbel function for minima with zero location parameter leads to the proposed model:

$$\log \Delta T^* = -\delta \log\left[-\log \Delta\sigma_a^*\right] = -\delta \log\left[-\log\left(\frac{\Delta\sigma_a - \Delta\sigma_{a0}}{\Delta\sigma_{aup} - \Delta\sigma_{a0}}\right)\right], \qquad (2)$$

where

$\Delta T^* = \Delta T/\Delta T_0$,

δ – is the scale parameter of the Gumbel distribution,

ΔT_0 – is a reference temperature that can be associated with a location parameter representing a constant temperature increment resulting from the elastic loading and the possible increase of temperature originated in the testing machine, both not due to the crack growth.

From solution eq. (2), the value of fatigue limit σ_{afTM} is determined as 97.69 MPa. The fitting curve is shown in Fig. 6.

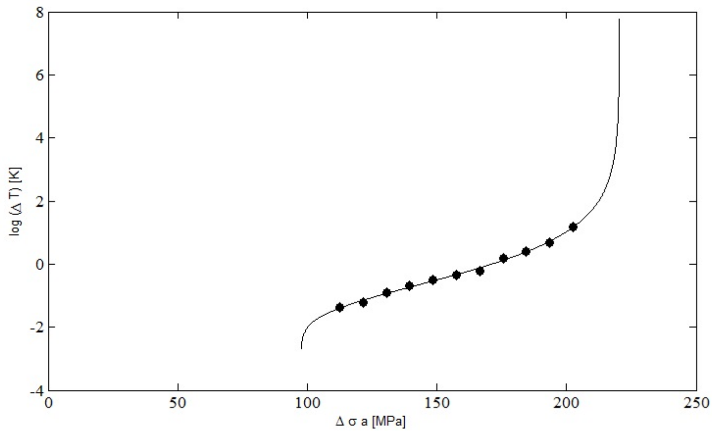

Fig. 6 The fatigue limit by the infrared thermography – method by Canteli et al. [3]

3.2 Comparison between the fatigue limit from infrared thermographic methods and from the traditional S-N field

Tab. 3 presents the comparison between the fatigue limit obtained from the traditional *S-N* curve σ_{afSN} and that predicted σ_{afTM} by applying different thermographic approaches. In last line of Table 3, the errors between the predicted parameters σ_{afTM} and traditional parameter σ_{afSN} are determined by the following formula:

$$\delta\% = \left|\frac{\Delta\sigma_{afSN} - \Delta\sigma_{afTM}}{\Delta\sigma_{afSN}}\right| \times 100. \qquad (3)$$

Tab. 3 Fatigue limits from thermographic methods and from traditional *S-N* field and their resulting errors referred to that from traditional *S-N* field for Al 2024.

AL 2024	*S-N* curve	Ristitano et al.	Second Risitano et al.	Canteli et al.
Fatigue limit σ_{af} [MPa]	100	99.97	95	97.69
Error δ (%)	-	0.03	5	2.31
Time of the measurement [day]	14	1	1	1

Low values of errors between the predicted values and the reference (conventional) one are possibly due to the limited sensitivity of the testing system and the scattering feature of the experimental data. During the infrared thermographic tests, the superficial temperature increments under cyclic stress levels take on lower scattering than the conventional fatigue life, which decreases the errors of fatigue life predictions.

Note that the infrared thermography can not only predict the fatigue behavior of materials with a limited number of specimens in a short test period, but also can visibly identify the serious fatigue damage in real time by observing the changes of the hottest zone on the specimen surface.

4 CONCLUSIONS

In this paper, the infrared thermography has been applied to study the fatigue behavior of Al 2024, and to detect the fatigue damage processes of the cylindrical specimen. The temperature evolution due to the localized plastic deformation during the fatigue evolution process is closely associated with the fatigue limit and the fatigue life of materials and components according to the application of the infrared thermography. The fatigue behavior, represented by the fatigue limit and the fatigue *S–N* curve, is able to be rapidly determined with a limited number of specimens in a short test period, whereas a good agreement between the predicted values and the traditional results is achieved. The infrared thermography enables us to visibly identify the temperature increments on the hottest zone induced by the irreversible plastic strain during fatigue loading. By qualitatively analyzing the evolution of the hottest zone on the specimen surface, it is possible to avoid sudden fatigue fracture in practical engineering.

Note that, traditional fatigue tests are extremely time consuming, so that, alternatively, innovative tests based on the thermographic method turn out to be very useful, due to its flexibility and rapidity in giving reliable results.

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