Investigation of Fatigue Crack Initiation and Growth in 35CD4 Steel by Infrared Thermography

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ABSTRACT. *The present work is devoted to the investigation of middle-cycle fatigue ($\approx 10^5$ cycles). Smooth specimens made of 35CD4 quenched and tempered steel were loaded in fully reversed plane bending. Temperature fields were recorded with an infrared camera. Our experimental results show that the local heating of metal under fatigue loading is a sensitive and accurate enough manifestation of damage initiation. The appearance of mesoscopic defect structures leads to the time correlated thermal behavior of adjacent points in the recorded temperature field. It is shown that the time evolution of the spatial standard deviation of the temperature can be used to investigate the defect collective properties, the damage localization and to monitor both the initiation and the current location of fatigue crack tip.*

INTRODUCTION

The microstructure evolution of metallic materials under cyclic loading has been the object of intensive study during all the last century. It has been shown that the fatigue of metal is accompanied by the appearance of specific dislocation patterns such as veins-channels structures, persistent slip bands-matrix structures, labyrinths, shell structures [1]. This evolution simultaneously involves a great number of strong non-linear interacting defects at different scales. This leads to the specific changing of the macroscopic material response. An adequate description of these processes should use the knowledge of the role of more than a single relevant length or time scale.

This description requires both the detailed theoretical investigation of the non-linear laws of the defect kinetics and the development of new experimental techniques. One powerful way to obtain the nonlinear kinetic equations for the defect density based on the statistical physics approach was proposed in [2]. To progress in the development of this approach and to identify additional constants in the constitutive equations we strongly need the detailed investigation of the processes of plastic deformation, damage and failure responses in a large range of loading rates. The localization of the plastic deformation and the initiation of fatigue cracks create an heterogeneous distribution of heat sources on a specimen surface that makes interesting the investigation of the infrared radiation of the surface. In the recent years, the progress in the development of new infrared cameras allows to use infrared thermography as a powerful, non destructive, non contact technique for the investigation of the fatigue characteristics of materials [3,4].

The present work is devoted to the investigation in middle-cycle fatigue (around 10^5 cycles) of the collective and stochastic properties of defect ensemble at the surface of smooth specimens made in 35CD4 steel, loaded in fully reversed 4 point plane bending. Temperature evolution has been recorded with an infrared camera (Jade III by CEDIP, thermal resolution: 0.1 mK and maximum framing rate: 500Hz). The aim of this paper is to find an appropriate technique for detecting in space and in time the plastic strain localization, initiation and propagation of small fatigue cracks by monitoring the specific temperature evolution on the specimen free surface.

THEORETICAL BACKGROUND

The development of the thermo-elastic-plastic equations in the case of small deformation can be made as follow. Let us assume that we can describe the thermodynamic process under investigation using the following thermodynamic quantities: r - the volumetric mass; e - the specific internal energy; e, s - the strain and stress tensor, consequently (in this case $e=\frac{1}{2}\left(\nabla u+\nabla u^T\right)$, with u - the displacement vector, s - the Cauchy stress tensor); r - the heat supply; q - the heat flux vector per unit area; F - the Helmholtz free energy; S - the specific entropy; T - the absolute temperature.

Let start from the fundamental equations of continuum mechanics [5] postulating for the balance of energy (first law of thermodynamics), kinematics of media, direction of the thermodynamic process (second law of thermodynamics):

$$r\left(\dot{F}+S\dot{T}+\dot{S}T\right)=s:\dot{e}+rr-\nabla\cdot q\,,\qquad e=e^e+e^p+b\left(T-T'\right), \tag{1}$$

$$t:e^p-q\frac{\nabla T}{T}\geq 0\,,$$

where $\nabla=\left(\frac{\partial}{\partial x_1},\frac{\partial}{\partial x_2},\frac{\partial}{\partial x_3}\right)$, the superposed dot stands for the material time derivative , e^e - the elastic strain tensor; e^p - the plastic strain tensor; b - the tensor of thermal expansion; T' - the reference temperature, $t=s-r\frac{\partial F}{\partial e^p}$ - the tensor of energy dissipation.

Using the determination of the stress tensor and the specific entropy, first equation in (1) can be written as follow:

$$r\left(\frac{\partial F}{\partial e^p}-T\frac{\partial^2 F}{\partial T\partial e^p}\right):\dot{e}^p-T\frac{\partial s}{\partial T}:\dot{e}^e-rT\frac{\partial^2 F}{\partial T^2}\dot{T}+T\dot{s}:b=s:e^p-\nabla\cdot q+rr\,. \tag{2}$$

Assuming the following relations for the heat flux vector and the Helmholtz free energy of the system

$$q=-K\nabla T\,,\ F=F_0+\frac{1}{2}e^e:E:e^e+c_vT\ln\left(\frac{T}{T'}\right)+f\left(p\right), \tag{3}$$

equation (2) can be rewrite as (4):

$$rc_v\dot{T}=rr-K\nabla\cdot\nabla T-Tb:E:\dot{e}^e+s:\dot{e}^p-r\frac{\partial f\left(p\right)}{\partial p}:\dot{p}\,. \tag{4}$$

One possible way to determine the function $f(p)$ can be based on the statistical description of the typical mesodefects evolution (microcraks, microshears). According to the statistical approach developed in [2] we can introduce the macroscopic tensor $p_{ik} = n\langle s_{ik} \rangle$ obtained by the averaging of the "microscopic" tensor $s_{ik} = 1/2s(v_i l_k + l_i v_k)$ (here $\vec{n}$ - slip plane of a microscopic shear; $\vec{l}$ - a unit vector in the direction of shear ; s - the shear intensity of a microscopic shear). In case under investigation the macroscopic tensor $p_{ik} = n\langle s_{ik} \rangle$ coincides with the deformation caused by the defects and include the full plastic deformation and the part of elastic deformation of solid lattice caused by the defects growth. Using the solution of the statistical problem [2] we can write the macroscopic one dimensional approximation of the function $f(p)$

$$f(p) = A(d)p^2 - Bp^4 + C(d)p^6 - De^e p\,, \tag{5}$$

where δ is a structure sensitive parameter (δ can be determined as a ratio of the characteristic size l_n of the defect nucleus and the average distance l_c between defects [2]).

The function (5) presents the nonlinear response of solid on defect grow. The mathematical properties of expansion (5) was investigated in details in [6]. This investigation shows the possibility of an excitation of collective modes into defect ensemble and the emergence of deterministic chaos properties in material response [6-8]. Equation (4) allows us to divide the full mechanical work produced by the plastic deformation $s : e^p$ into two parts: the energy spent in the modification of the material microscopic structure ($r\dfrac{\partial f(p)}{\partial p} : \dot{p}$ is the time derivation of the energy spent for changing of the material structure) and the second one spent in heating. We can use (4) as a base for the application of infrared scanning in different engineering and scientific problems.

EXPERIMENTAL PROCEDURE

The material under investigation is 35CD4 steel. This material was investigated in [9]. The chemical composition and mechanical properties are given in Tables 1 and 2, respectively. The grain size of this steel is around 10 µm. The specimens (Fig.1.) were machined from round heat treated bars. The treatment procedure was as follow: 30 minutes in oven at 850°C, then quenched in oil, then 1 hour at 550°C, and leave in air for cooling. The central portion of the specimen was 13x15x30 mm. Before experiments all the specimens were polished with emery paper and diamond powder up to grade 1µm. The specimen was loaded in fully reversed sinusoidal plane bending with a resonant electrodynamic fatigue testing machine (loading frequency ~56 Hz). The tests series were carried out with nominal stress amplitude in the range from 200 to 650 MPa.

Table 1. Chemical composition of 35CD4 steel (in wt%)

C%	Mn%	Si%	S%	P%	Ni%	Cr%	Mo%
0.37	0.79	0.30	0.010	0.019	<0.17	1.00	0.18

Table 2. Mechanical properties of the 35CD4 quenched and tempered steel

Young modulus (MPa)	Yield stress $Re_{0.2}$ (MPa)	Maximum tensile strength (MPa)	Fatigue limit for 10^7 cycles (MPa)	Fatigue limit for 10^5 cycles (MPa)	Fracture elongation (%)
$2\ 10^5$	950	1068	525	660	11.5

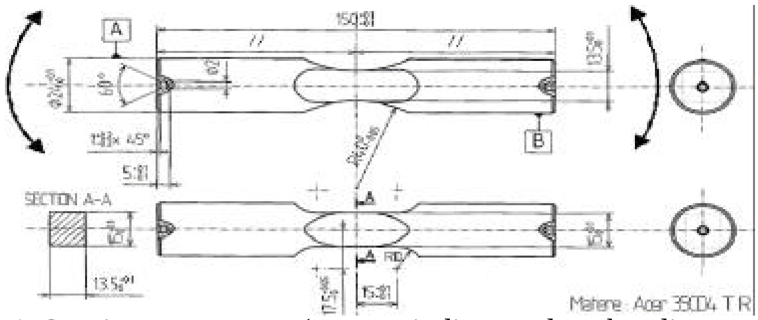


Figure 1. Specimen geometry (arrows indicates plane bending moment).

The tests were automatically stopped if the resonance frequency decreases more than $\approx 10\%$. During these tests, an infrared camera (CEDIP Jade III) was used to record the evolution of the temperature field of the specimen surface.To investigate the peculiarities of the temperature evolution two types of records of were used. In the first case the framing was synchronized with the maximum of the loading. In the second one the framing was made with maximum possible frequency of the camera (up to 500 Hz).The duration of the experiments presented in the paper are 10-15 minutes about. During this time the external temperature in laboratory changed less than 1°C. For longer tests one have to used some techniques for recording of external temperature or keeping this temperature equals to a constant.

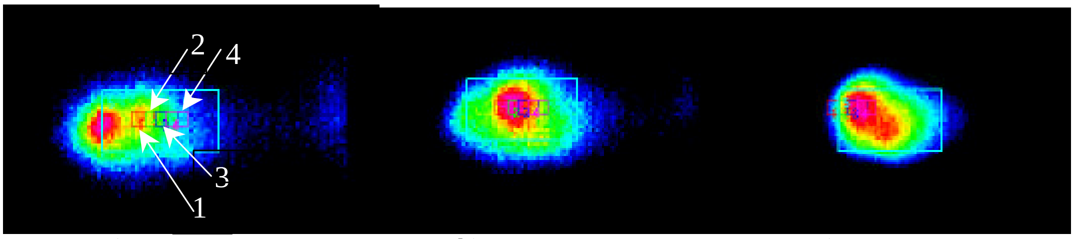
EXPERIMENTAL RESULTS

The emergence and interaction of mesoscopic structures developing on the different scale levels should be accompanied by the collective behavior of defects and have to lead to the appearance of the correlation in the time evolution of adjacent points in the temperature field. To investigate this phenomenon we have calculated the dependence in time of the spatial standard deviation of temperature field (SDT).

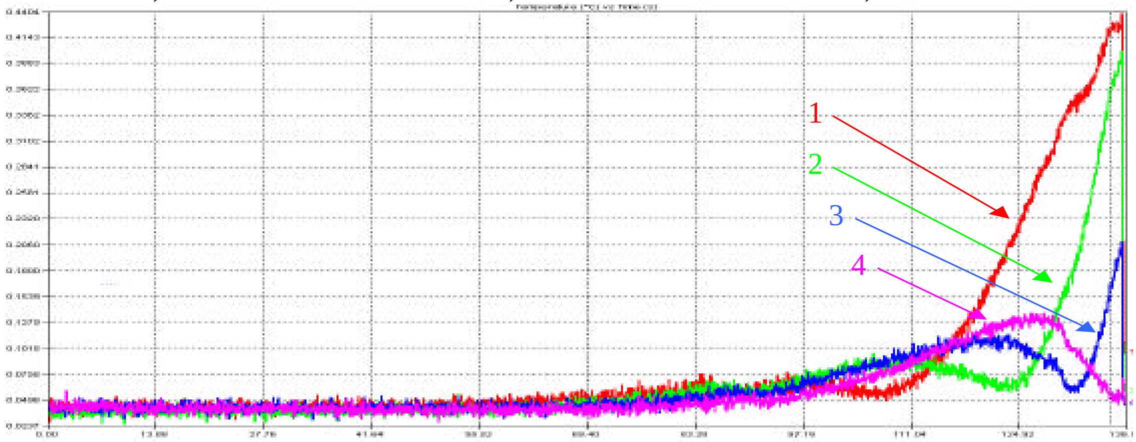
This spatial standard deviation was computed according to the following procedure. An experimentally obtained thermal signal from some point $x=(x_i,y_j)$ can be written as vector $T(x)=[T(t_1,x),T(t_2,x),...,T(t_N,x)]^T$. A posteriori, i.e. after macrocrack initiation detected by the resonance frequency drop of the testing machine, we located the spatial area Ω containing several points (N_p from 9 to 100) near a hot spot in the temperature field then SDT was calculated as follows

$$SDT^2(t_i)=\frac{1}{N_p-1}\sum_{x\in\Omega}\left(T(t_i,x)-\bar{T}(t_i)\right)^2,$$

where N_p is number of pixels in the area Ω; $\bar{T}(t_i)=\frac{1}{N_p}\sum_{i=1}^{N_p}T(t_i,x)$ is the mean value of the temperature at time t_i.



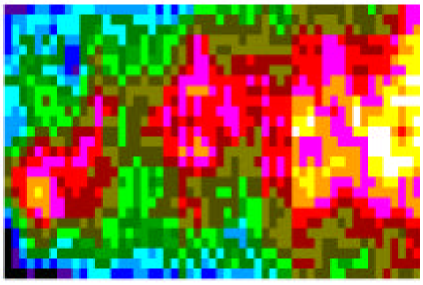
a) t=98 sec b) t=111 sec c) t=127sec



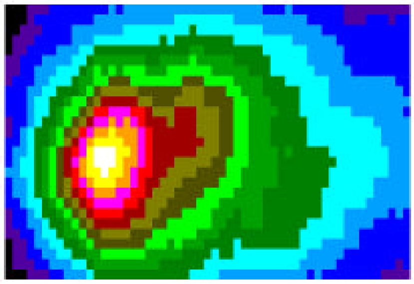
d)

Figure. 2.. Locations of hot spot (a,b,c) and the corresponding evolution the spatial temperature standard deviation versus time (d).

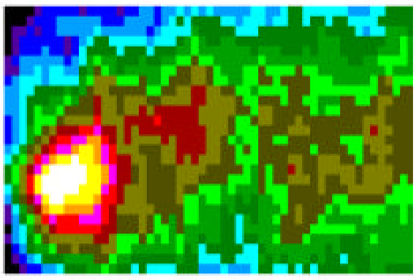
As is shown in Fig. 2, the SDT-time curve exhibits a negative slope manifesting the beginning of correlation behavior of adjacent points in the temperature field. This behavior can be observed before the sharp change of the resonance frequency of bending (approximately when the resonance frequency change by 1-2%) and can be used for determination of localization of the process zone during the small fatigue crack propagation. Fig. 3 presents several frames from the last 2500 cycles of the experiment at stress amplitude 650 MPa. Life time was 83300 cycles up to crack initiation detected with the testing machine. The location of the area under investigation is fixed in space. The real size of the corresponding area on the specimen surface is about 2.8x5.5 cm. The temperature distribution and a posteriori surface pattern investigation allows us to conclude that we observed the initiation (a), propagation (b, c) and jumping (d) of fatigue crack. Fig. 3. shows that the fatigue crack starts to propagate from the left and during the propagation it jumps.



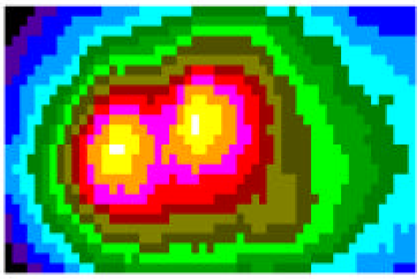
a) N=80830 cycles (≈1616 sec), maximum temperature 28.7° C, minimum 28.4° C



c) N=82550 cycles (≈1651 sec), maximum temperature 30.9° C, minimum 29.9° C.



b) N=81650 cycles (≈1633 sec), maximum temperature 29.1° C, minimum 28.8° C.



d) N=82785cycles (≈1656 sec), maximum temperature 31.4° C, minimum 30.7° C.

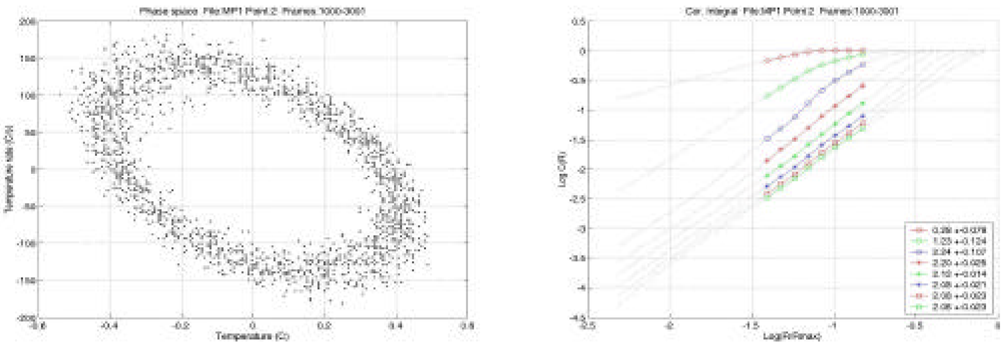
Figure. 3. Fatigue crack propagation and jumping. Size of area is about 2.8x5.5 cm.

To illustrate clearly a connection between the SDT evolution versus time and the position of the area under investigation, let us locate several areas as shown in fig 2 and compute the time evolution of the temperature standard deviation in these zones. The arrangement of small areas were fixed in space.

From the analysis of fig 2 we can conclude that:

- when the crack is outside the area and moves to this area, the SDT in this area increases;
- when the area is located into the process zone (zone near the crack tip where stress is more that a critical value [7]) the SDT decreases, this corresponds to the correlation temperature behavior of adjacent points;
- when the crack tip is located into the area, the SDT sharply increases, that corresponds to an existence into the area of points with very different temperature kinetics (points into the process zone and points unloaded by crack).

The repeatable character of the process under investigation, the excitement of the defects on set spatial scales, the strong defect interaction and the transition of the energy from one structural scale to another allow us to imagine that some peculiarities of the process under investigation could be similar than the peculiarities of the turbulence process in liquid and applied the Grassberger-Procaccia algorithm [10] to investigate damage localization and the stochastic properties of the defect ensemble evolution. The stochastic properties of the temperature time evolution (one pixel represents approximately 100x100*mm* on the specimen surface) was analyzed by using the Grassberger and Procaccia algorithm [10].



a) b)

Figure 4. Determination of the correlation dimension for local temperature signal. Phase portrait (a) and correlation integral (b) (stress amplitude is 480 Mpa).

To investigate the small disturbances caused by the local plastic flow and/or damage kinetics, several films were made with a framing frequency of 400 Hz for different stress amplitude (from 400 to 610 MPa). The duration of each recorded signals was about 20000 cycles, the stress amplitude during each test was increased after each 25000 cycles accordingly to the plan: 400 MPa, 480 MPa, 500 MPa, 535 MPa, 610 MPa. For each film we have investigated 5 different local time signals and mean time signals obtained by space averaging on the area with size ~ 1 cm^2.

The most interesting results were obtained for the stress amplitude 480 MPa. It was established that for this stress level the biggest difference between mean and local signal is observed. The correlation dimension of the local signal is about 2.10±0.02. This can show the existence of the deterministic chaos properties [11] in the damage evolution under fatigue loading. It is very important to note that the surface profile measurements made in [12] show that under the stress amplitude 480 MPa the intensive development of PSB on the specimen surface can be observed. The observation of specific temperature evolution and development of PSB on the specimen surface which initiate at 420 MPa [12] allow us to understand the stress amplitude 420 MPa as the threshold stress proposed in [13] for which damage can initiate and grow up to a macrocrack and stop on microstructure barriers. Other investigation has to be done in this way.

CONCLUSIONS

In our tests of 35CD4 smooth steel specimen the damage localization, fatigue crack initiation and jumping-like propagation were observed using the infrared camera. Our experimental results show that the local heating of metal under fatigue loading is a sensitive and accurate enough manifestation of damage initiation. The appearance of mesoscopic defect structures consisting of strong interacting defects predicted in [2] and described in framework expansion (5) leads to the correlated thermal behavior of adjacent points. This behavior can be determined by monitoring the time evolution of the spatial standard deviation of temperature.

After the end of fatigue life (macrocrack initiation) the standard deviation was calculated in several small areas located near hot spots in the recorded temperature field. It is shown that the damage evolution and fatigue crack propagation lead to the sharp changing of the standard deviation evolution. The appearance of increasing and decreasing parts in the dependence of the standard deviation on time allow us to determine the beginning of the defect collective behavior leading to a macrocrack before the sharp changing of the resonance frequency of the specimen.

The progress in understanding the connection between SDT evolution and damage initiation could help us to develop a new technique for early detecting the peculiarities of defect evolution leading to a macro crack initiation. For instance, in future, if the calculation speed of computers will be enough, we can imagine a system which monitor the specimen surface and compute in real time the SDT evolution in time of different areas of the specimen surface and thus detect crack initiation when the SDT will change manifesting the beginning of specific defect behavior.

Finally, the Grassberger-Procaccia algorithm was applied to investigate of the damage localization and the stochastic properties of the defect ensemble evolution. Our preliminarily results show the existence of fractional (no integer) correlation dimensionality (2.10±02) of the thermal evolution at the specimen surface for the stress amplitude 480 MPa (below the conventional endurance limit 525 MPa) under fatigue loading.

REFERENCES

1. Suresh, S. (1991) *Fatigue of Materials*. Cambridge University Press.
2. Naimark, O.B. (1998) *JETP Letters* **67** 9, 751-757.
3. La Rosa, G. and Risitano, A. (2000) *International Journal of Fatigue*, **22**, 1, 65-73.
4. Luong, M.P. (1995) *Nuclear Engineering and Design* **158**, 363-376.
5. Sedov, L. (1975) *Mecanique des milieux continués*, Editions «Mir», Moscow.
6. Naimark, O.B. (2002) *Proceedings of International Conference on New Challenges in Mesomechanics*, Aalborg University, Denmark, 89-95.
7. Naimark, O.B., Davydova, M.M., Plekhov, O.A. and Uvarov, S.V. (1999) *Physical Mesomechanics*, **2**, 3, 47.
8. Plekhov, O.A., Eremeev, D.N. and Naimark, O.B. (2000) *J. Physique IV Colloq C.* **10**, 811.
9. Vivensang, M. (1994) *Comportement en fatigue de deux nuances d'acier 35CD4*. Thèse de l'ENSAM, Bordeaux.
10. Grassberger, P. and Procaccia, I. (1983) *Physica* **9D**, 189-208.
11. Berge P., Pomeau Y., Vidal Ch. (1988) *L'Ordre Dans Le Chaos.* Hermann Press.
12. Uvarov S., Mikhailov E., Plekhov O. and Palin-Luc T. (2003) *Proceedings of International Conference The Mechanical Behavior of Materials*, Geneva.
13. Palin-Luc, T., Lasserre S. and Berard, J.-Y. (1998) *Fatigue & Fracture of Engineering Materials & Structures* **21**, 191-200.