Study of Crack Propagation by Infrared Thermography during Very High Cycle Fatigue Regime

N. Ranc[1], L. Illoul [1], D. Wagner[2], P. C. Paris[3], C. Bathias[2]

[1]LMSP, Arts et Métiers ParisTech, 75013 Paris, France; [2]LEEE University Paris X, 92410 Ville d'Avray, France; [3]LAMEFIP ENSAM Bordeaux, 33405 Talence, France

Abstract: In this study, the power dissipated into heat during the propagation of a fatigue crack in very high cycle fatigue regime is studied by infra-red pyrometry on a bearing steel. The thermal results show a significant and very local increase in the temperature just before the fracture. In order to better understand the fish eye propagation of the crack which occurs during very high cycle fatigue regime, a thermomechanical model was developed. To describe the evolution of the growth rate law of the crack, a Paris law was used. The fatigue crack is modelled by a circular ring heat source whose radius increases in time. The thermal problem is solved numerically by finite element method. The results show a good correlation with the experiments. The temperature evolution allows to detect experimentally the initiation of the crack propagation. These results show that in very high cycle regime, the propagation stage of the crack constitutes a small part of the lifetime of the specimen.

1 Introduction

High cycle fatigue has become a major concern in design and durability of the engineering components. In the lifetime of mechanical structures, many elements can be loaded beyond 10^7 cycles. For several years, many researchers have been thus exploring the very high cycle fatigue regime (VHCF) [1]. It has been found that the fracture mechanisms associated with the VHCF are somewhat different from those known more classically in high cycle fatigue (HCF). For example, it was shown that fatigue failure can occur at values of cycle exceeded 10^7 cycles for stress level lower than the conventional high cycle fatigue limit. According to the experimental observations derived from the literature, crack initiation in very high cycle fatigue regime usually seems to occur inside the sample and not on the surface if there are inclusions or porosities in the metal. The fracture initiation is characterized by the formation of a fish eye. The various mechanisms of the crack initiation and crack propagation are not currently very well known because of the experimental difficulties like very long test duration or observation inside the metal during test.

The main objective of this paper is to use thermal measurement during fish eye propagation in ultrasonic testing in order to understand better the fracture mechanisms in the VHCF regime.

2 Experimental study

Ultrasonic fatigue tests are carried out on a high strength steel with 0.2% carbon content [2]. The loading frequency is 20kHz and the stress ratio R is equal to -1. The geometry of the specimen and the ultrasonic fatigue machine are presented respectively on figure 1 and 2.

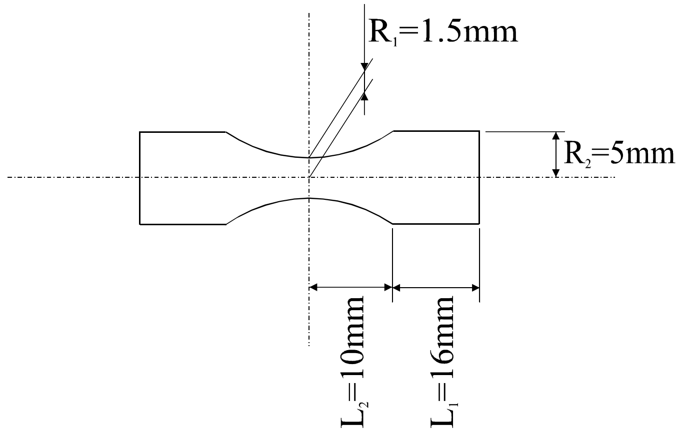


Fig 1. Geometry of the specimen for ultrasonic fatigue tests.

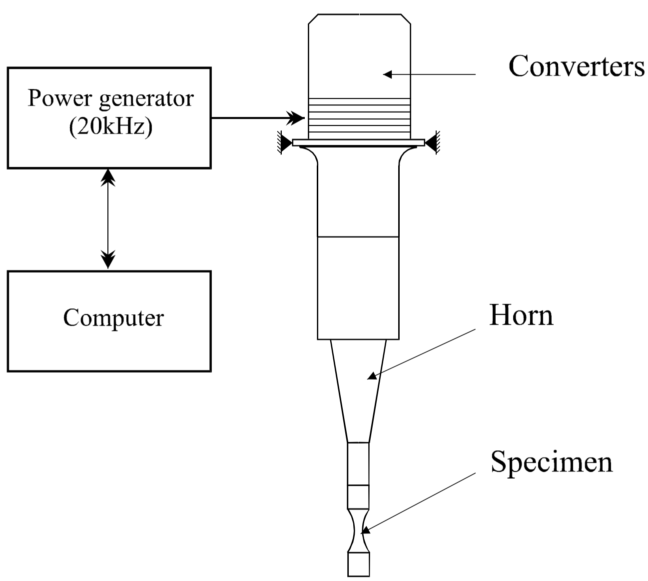


Fig 2. Ultrasonic fatigue machine.

In order to measure the temperature field on the specimen surface and therefore to detect the associated plastic deformation, an infra-red camera is used [3]. The spectral range of the camera is in the near infrared domain (between wavelengths 3.7µm and 4.8µm). The aperture time is 10µs and the acquisition frequency is 100Hz. The space resolution is 0.12mm per pixel. All the useful parts of the specimen can be visualized thanks to the large size of the matrix (64 per 80 pixels). The camera is calibrated on a black body in a temperature range between

50°C and 400°C. The specimen was covered with a fine coat of strongly emissive black paint in order to limit the errors associated with the emissivity of the surface.

One test is carried out with stress amplitude of 335MPa. During this test, the fracture takes place at 8.37×10^7 cycles. In the beginning of the test there is a homogeneous and rapid increase in the surface temperature of the specimen (around 10s) and a stabilization toward a temperature of approximately 233°C. Figure 3 shows the maximum temperature evolution on the specimen surface near the end of the test. It is noted that an abrupt increase in this temperature occurs just before the fracture. Thermographies of the figure 4 show the temperature field at various moments represented on the figure 3. The increase in the temperature is increasingly heterogeneous when one approaches the fracture.

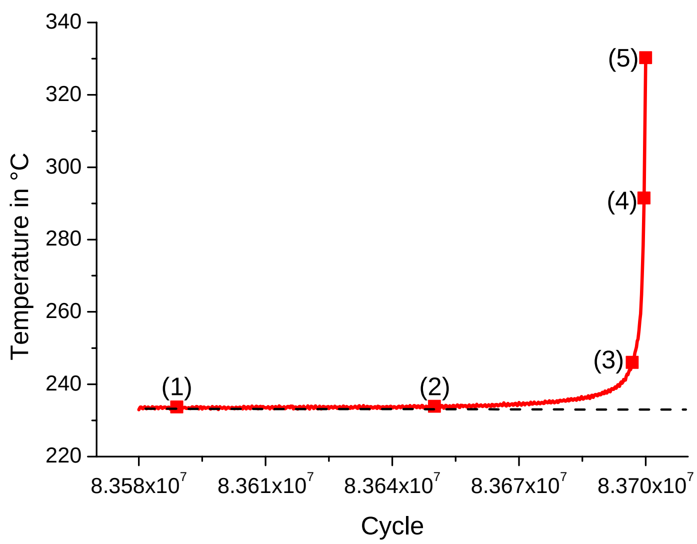


Figure 3. Temperature evolution on the specimen surface just before fracture.

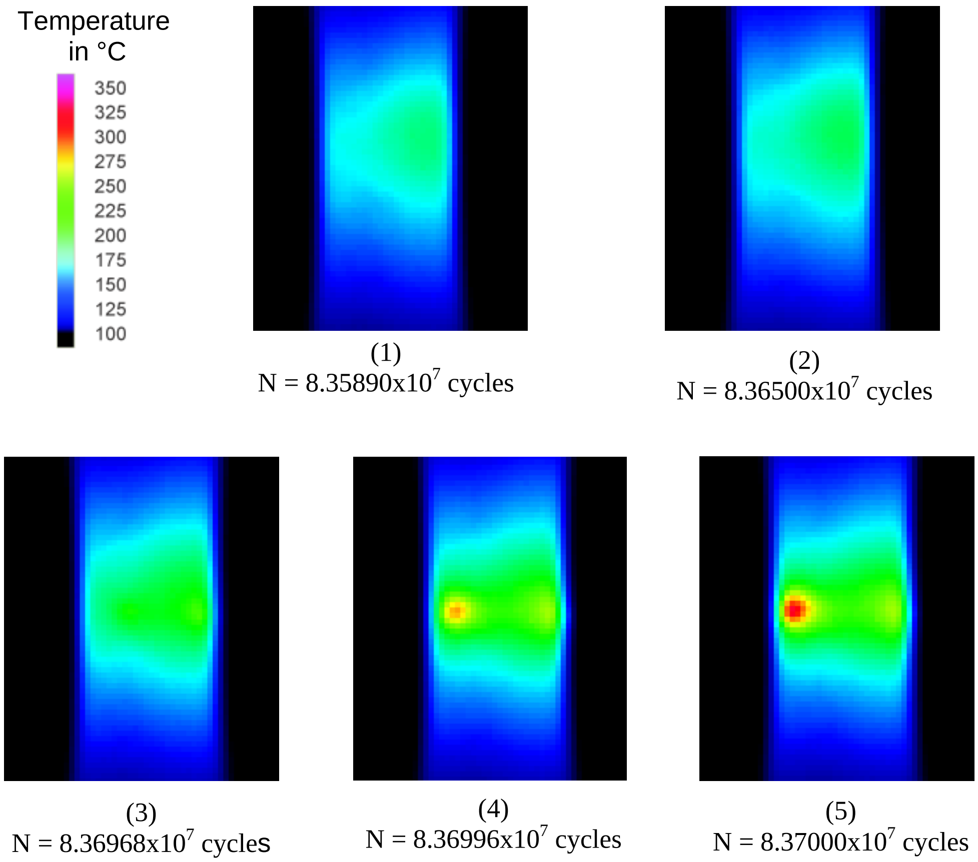
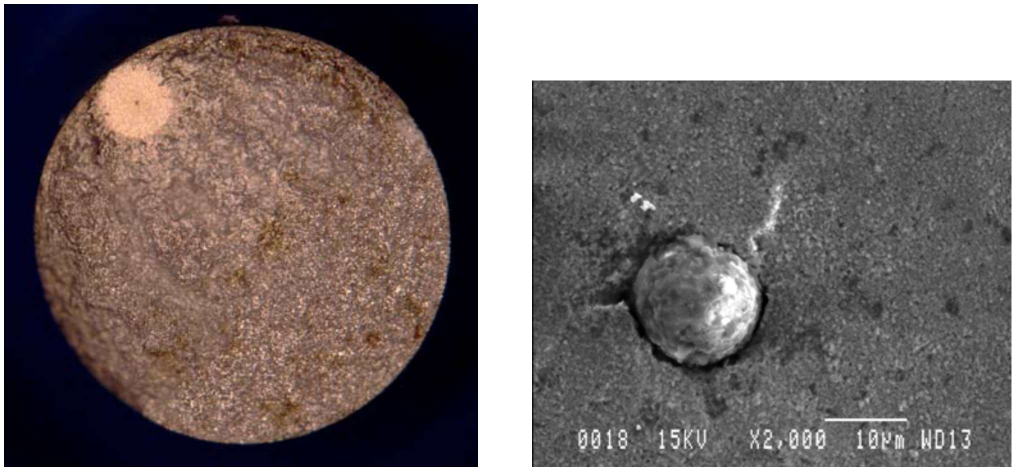


Figure 4. Temperature field on the specimen surface just before fracture.

A post mortem observation of the fracture surface (figure 5a) highlights a fish eye which is characteristic of the propagation of a circular crack from an inclusion during very high cycle fatigue fracture. This figure allows to estimate the eccentricity of the fish eye to be e = 0.8, which is define as the ratio of the distance between the center of the specimen and the center of the fish eye to the specimen radius. An observation by scanning electronic microscopy of the inclusion which initiated crack propagation allowed measurement of the average size of the inclusion (figure 5b). It gives us a_{int}=7.6µm.

3 Modeling and discussion

It is supposed that just before the fracture, this local increase of the temperature is associated with the propagation of a fatigue crack in the specimen. At each cycle the plastic strain at the crack tip creates a mobile heat source which is dependent on time. The temperature variation associated with this heat source is then observed by the infrared camera. The objective of our modeling is to predict the thermal effect associated with the propagation of the fatigue crack by using the crack propagation models available in the literature.



a) **b)**

Figure 5. Post mortem observation of the fracture surface
a) fish eye observation by optical microscopy
b) observation of the inclusion in the center of the fatigue crack.

3.1 **The model of crack propagation**

In order to describe the growth of the fatigue crack in the case of the very high cycle fatigue test, the Paris-Hertzberg-McClintock crack growth rate is used:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = b\left(\frac{\Delta K_{eff}}{E\sqrt{b}}\right)^3, \tag{1}$$

where E is the Young modulus and b the norm of the Bürgers vector and ΔK_{eff} the amplitude of the effective stress intensity factor.

On the threshold corner (figure 6), we have:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = b \quad \text{and} \quad \frac{\Delta K_0}{E\sqrt{b}} = 1. \tag{2}$$

The crack growth rate is thus written:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = b\left(\frac{\Delta K_{eff}}{\Delta K_0}\right)^3. \tag{3}$$

By supposing a circular crack with a radius a and neglecting the crack closure, we obtain:

$$\Delta K_{eff} = \frac{2}{\pi}\Delta\sigma\sqrt{\pi a}. \tag{4}$$

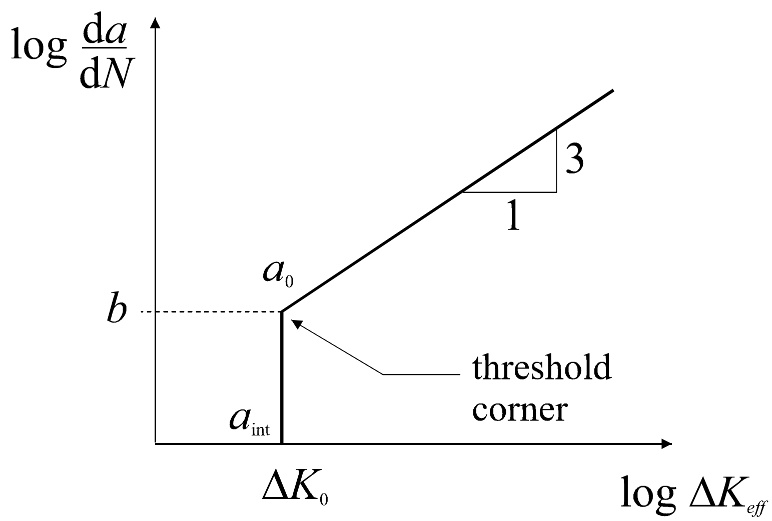


Figure 6. Crack growth rate according to the stress intensity factor.

Therefore:

$$\frac{da}{dN} = b\left(\frac{a}{a_0}\right)^{3/2} . \tag{5}$$

Integration of the last equation between a_0 (t=0) and a (time t), gives:

$$bft = (a_0)^{3/2}\int_{a_0}^{a}\frac{da}{a^{3/2}} = (a_0)^{3/2}\left[\frac{-2}{\sqrt{a}}\right]_{a_0}^{a} = 2a_0\left(1-\sqrt{\frac{a_0}{a}}\right), \tag{6}$$

with f the loading frequency ($dN=fdt$).

After inversion of equation 6, the evolution of a according to time is:

$$a(t) = \frac{a_0}{\left(1-\frac{t}{t_c}\right)^2} \quad \text{with} \quad t_c = \frac{2a_0}{bf} \tag{7}$$

In the experiment, a_{int}=7.6µm is measured (figure 5b) and $a_0=a_{\text{int}}/0.94$=8µm is estimated. Also t_c=4.4s is obtained (b=1.8Å). The crack growth is limited to t_f=3.6s which corresponds to the time when the crack reaches the surface of the specimen. The relation of equation 7 gives then a cycle number for propagation equal to $7.4\text{x}10^4$.

3.2 Calculation of the energy dissipated into heat during crack growth

The energy dissipated at each cycle per unit of crack length (noted E) is supposed to be proportional to the surface of the reverse plastic zone r_R [4]:

$$E = \eta r_R^{\;2} \,, \tag{8}$$

where η is a coefficient depending only on the material properties.

In plane strain, the radius of the reverse plastic zone is

$$r_R = \frac{\Delta K^2}{6\pi(2\sigma_y)^2} \,, \tag{9}$$

where ΔK is the amplitude of the stress intensity factor.

By replacing r_R, ΔK and $a(t)$, we obtain:

$$E = \eta \frac{a_0^{\;2}\Delta\sigma^4}{36\pi^4\sigma_y^{\;4}\left(1 - t/t_c\right)^4} \,. \tag{10}$$

We thus deduce the dissipated power per unit length of crack:

$$P = fE = \frac{P_0}{\left(1 - t/t_c\right)^4} \,, \quad \text{with} \quad P_0 = \eta \frac{f a_0^{\;2}\Delta\sigma^4}{36\pi^4\sigma_y^{\;4}} \,. \tag{11}$$

P_0 is a constant which will be identified from the experimental results.

3.3 **Modeling of the thermal problem**

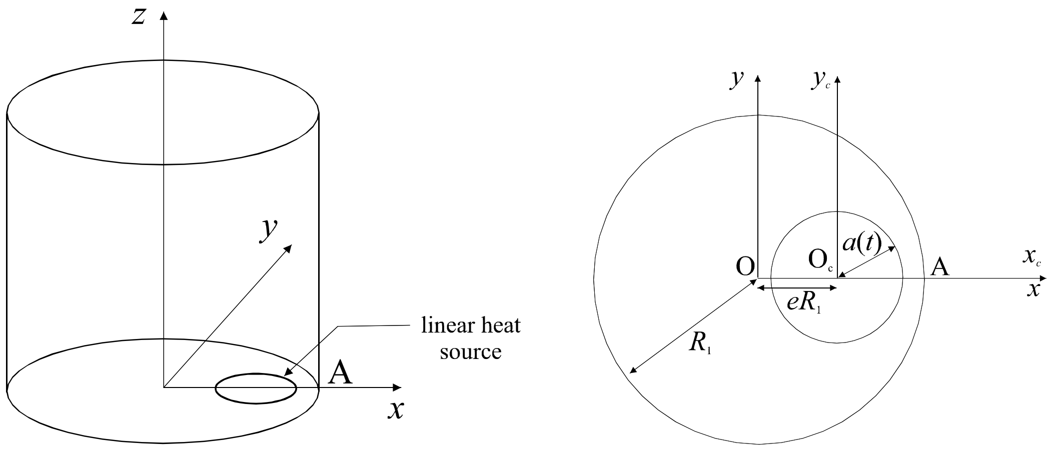
The specimen is modeled by a cylinder with a radius R_1 and a length 2ℓ where ℓ is taken equal to 5 times the radius (figure 7a). In a plane perpendicular to the specimen axis and located in the center of the specimen, we consider a circular crack with a radius $a(t)$ and eccentricity e=0.8 (figure 7b). The evolution of the crack radius and the power dissipated per unit length $P(t)$ are given in the previous paragraphs. For symmetry reasons, we consider only one half of the specimen.

The heat transfer equation gives

$$\rho C \frac{\partial T}{\partial t} = \frac{P(t)}{2}\delta(r_c - a(t))\delta(z) + \lambda \Delta T \,, \tag{12}$$

with ρ = 7800kgm^{-3} the density, C = 460JK^{-1}kg^{-1} the specific heat, λ = 52WK^{-1}m^{-2} the heat conductivity, r_c=eR_1 the position of the crack center, δ the Dirac function and Δ the Laplacian operator.

All of the boundary conditions are assumed to be adiabatic. Just before the crack propagation we consider that the initial temperature is homogeneous and equal to 233°C.



a) **b)**

Fig. 7. Geometry of the thermal problem
a) three-dimensional visualization
b) geometry of the circular crack.

4 Results and conclusion

The thermal problem is solved numerically by the finite element method. The finite elements used are linear and the integration scheme is implicit. The mesh is more refined in the zone close to the plane of crack propagation (100 elements are placed on the radius of the specimen). The calculation is made with an initial crack radius determined during the experiments (a_0=8μm) and a unit dissipated power per unit length P_0. It can be noticed that the temperature is proportional to the value of P_0. The real value of P_0 is also identified by a minimization method of the least squares of the difference between the maximum temperature measured in experiments and the temperature obtained with the model. It is found P_0=1.296x10^6Wm^{-1}.

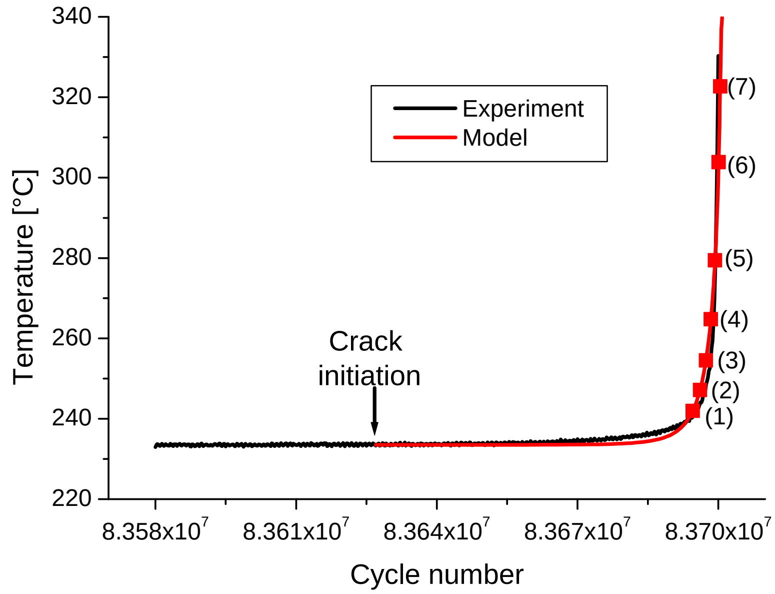


Figure 8. Evolution of the maximum temperature on the specimen surface.

Figure 8 shows the comparison of the evolution of the maximum temperature on surface of the specimen between the model and the experiments. The figure 9 represents the temperature field in the specimen at various times just before fracture. These various times are represented on the curve on figure 8.

It can be noticed the model predicts correctly the shape of the temperature evolution curve (figure 8). There is a good correlation of the model with experiment. These results show that in very high cycle regime, the propagation stage of the crack constitutes a small part of the lifetime of the specimen.

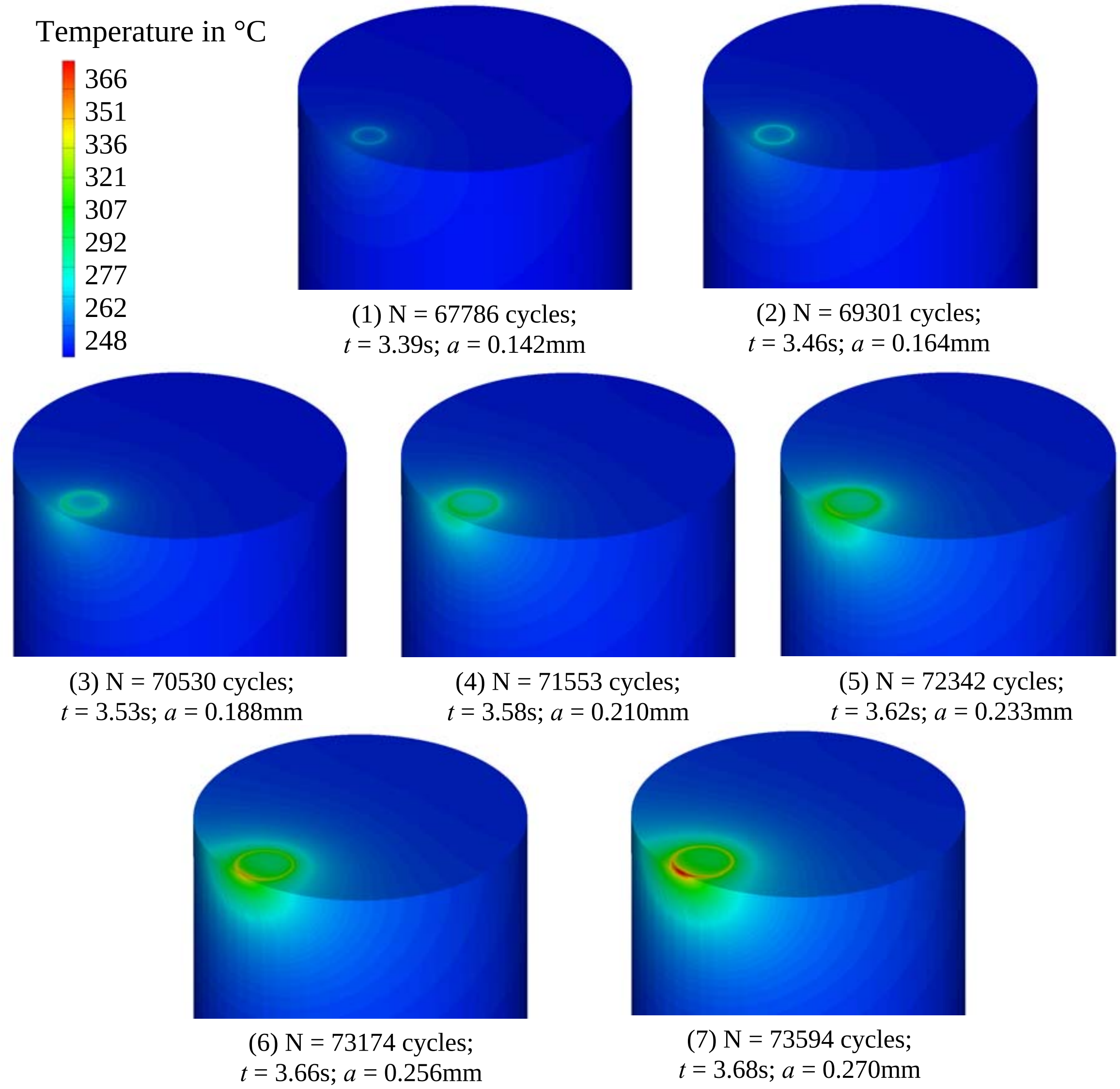


Figure 9. Temperature field in the specimen just before fracture.

REFERENCES

[1] H. Mughrabi, Int J Fatigue, 28 (2006) 1501-1508.

[2] C. Bathias and PC. Paris, Gigacycle fatigue in mechanical practice, Marcel Dekker, New York, 2005.

[3] D. Wagner, N. Ranc, C. Bathias, International Conference on Fatigue Damage of Structural materials VI, 17-22 septembre 2006, Hyannis, MA, USA.

[4] N. Ranc, D. Wagner, PC Paris, Acta Materialia, 56 (2008) 4012-4021.