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► **To cite this version:**

Minh-Phong Luong. Infrared thermographic scanning of fatigue in metals. Nuclear Engineering and Design, 1995, 158 (2-3), pp.363-376. 10.1016/0029-5493(95)01043-H . hal-04667425

HAL Id: hal-04667425

<https://hal.science/hal-04667425v1>

Submitted on 22 Aug 2024

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Infrared thermographic scanning of fatigue in metals

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The paper aims to illustrate the relevant use of infrared thermography as a non destructive, real-time and non contact technique (a) to observe the physical processes of damage, fatigue and failure on metallic specimens subjected to low-cycle rotating bending loadings, (b) to detect the occurrence of intrinsic dissipation and (c) to evaluate rapidly the fatigue strength of the tested materials. In addition, this infrared thermographic technique readily describes the damage location and the mechanism of the structure failure.

1. Introduction

The phenomenon of progressive strength deterioration caused by the action of repeated load cycles is referred to as fatigue.

The first experimental studies were carried out in 1829 in Germany on steel chains subjected to 100 000 repeated tensions at a frequency of about 10 min^{-1} . The rapid development of railway networks in the middle of the 19th century justified numerous studies on the techniques of fatigue limit determination in England, USA, France and Germany (Cazaud, 1948). The following most striking features of fatigue phenomena have been recognised and described (Orowan, 1938).

(1) *The quasi-brittle nature of fatigue fracture.* A ductile metal can break in a fatigue test without any appreciable external deformation, like a brittle material. Fine cracks and faults, which would not influence noticeably the static strength, sub-

stantially impair its fatigue limit.

(2) *Internal distortions.* In spite of the possible absence of any external deformation, heavy local distortions have been observed microscopically on metals subjected to fatigue tests (Ewing, 1902).

(3) *Existence of safe ranges.* For a fixed mean stress of the cycle, the number of cycles, that the material can withstand, increases rapidly with decreasing range of stress.

In recent years, fracture mechanics has become the primary approach to controlling brittle fracture and fatigue failure in structures. Experimental methods, which have been used to obtain the fatigue characteristics of materials, usually correlate the fatigue life of a smooth specimen under uniaxial stress conditions with either plastic strain or stress amplitude. Multiaxial fatigue assessment is then carried out with the help of an appropriate rule or criterion that reduces the complex multiaxial loading to an equivalent uniaxial loading. In

these approaches, the relationship between the cyclic stress, plastic strain and the fatigue damage process is usually overlooked (Morrow, 1965). Until now, the fatigue testing of industrial components or structures is a time-consuming and costly operation that influences to a great extent the time to market the manufactured product.

A very interesting question is raised: How can we provide reliable estimates of long fatigue lives on the basis of short-term data?

Many attempts have been devoted to this subject and methodologies were developed and proposed to overcome the problem: for instance, increasing of load levels and frequency, reduction of non damaging events, etc. The multiplicity of the proposed fatigue evaluation techniques testifies to the complexity of the problem and lack of an accepted unified approach. The challenge is to define a damage parameter that can be used to describe both the initiation and propagation phases of the fatigue phenomenon.

This paper emphasizes the application and use of infrared thermography to damage and fatigue evaluation of metallic materials, and subsequently to non destructive testing and integrity control on steel structures.

2. Fatigue and endurance of materials

When subjected to cyclically varying loads, metals break at stresses that are much lower than the ordinary fracture stress measured under static conditions. This loss of strength under alternating load conditions is called fatigue. In typical fatigue behaviour, the algebraic difference S between the maximum and the minimum stress of the cycle decreases with the number N of cycles that the material can withstand, according to a curve whose general shape is the Wöhler $S-N$ endurance curve. In cyclic loading, a material can safely support a given peak stress amplitude for only a specified number of cycles, given by the endurance curve, before it breaks. In some cases, the endurance curve may level off for a limiting stress amplitude called the fatigue endurance limit, below which the solid can support the load indefinitely without danger of fracture.

The most common method of obtaining fatigue endurance data is the rotating beam test. The rotating specimen is loaded in bending so that the peak stress alternations are experienced only at the outer edge of the cross-section.

The local nature of the phenomenon of fatigue failure makes it necessary to trace carefully the path which the applied loads take within the structure, because a fatigue crack can start in one small region of high alternating stress and can lead to complete failure even though the rest of the structure is very strong. The loads must be traced through the structure to the subcomponents, and the stress distribution within the subcomponent must be analysed to find the critical regions of high stress. It has been thought (Feltner, 1961), that the phenomenon of the fatigue damage is primarily controlled by the stress and plastic strain or the irrecoverable plastic strain energy per load cycle. Each material has a capacity to absorb a certain amount of energy and when this limit is attained, fatigue failure results. The fatigue failure is sometimes defined in terms of a crack length for the load-controlled tests, and a drop in the peak stress for the strain-controlled tests.

The main problem in fatigue is not that of crack propagation as is frequently assumed. It is a plausible conclusion which can be supported by considerations of stability (Irwin, 1965), that an existing crack of critical size will have a tendency to spread under the action of consecutive stress cycles. A fatigue theory based on crack propagation, however, evades the main problem, which is why cracks of any size, however minute, should form at all under repeatedly applied stresses of an intensity that, in a single application, produced neither damage nor even significant deviation from overall elastic response of the material.

3. Quantitative measurement of damage

The term damage is commonly used in different ways by different investigators to describe (1) crack initiation, fatigue lifetime and the early microcracking stages of crack growth, and (2) fatigue damage associated with macroscopic fa-

tigue crack extension. Continuum mechanics assumes that damage is induced by the initiation and growth of microcracks and microcavities. Damage theories usually rely on assumed discontinuous phenomena at the microscopic scale (Bui, 1987). Damage parameters, considered as internal variables, are introduced according to the following main approaches.

Effective stress

In order to develop the concept of an effective stress, Kachanov (1958) introduced a continuous variable D related to the scalar density of defects. The elastic body is assumed to contain many cracks. The empty phase comprising the cracks has zero volume fraction. It has been thought that the stiffness reduction produced by the cracks is due to the stress singularities at the crack tips. As a result of this, the stress energy for prescribed surface fractions is increased by a finite amount relative to the stress energy of the body without cracks. Thus the cracks increase the compliances and decrease the stiffnesses. This has been the starting point of damage theories developed for analysing fatigue in metals, creep and creep-fatigue interaction (Lemaitre, 1978).

Plasticity formalism

The plasticity formalism describes the inelastic behaviour of progressively fracturing solids by introducing the concept of fracturing stress or fracturing strain. The elastic-plastic fracturing model combines the elastic-plastic law and the elastic-brittle law (Dougill, 1983). Taking into account the most fundamental aspects of inelastic deformation and neglecting the details at the microstructural level, Mroz (1986) suggests phenomenological constitutive models that are widely used in engineering applications.

Micro-mechanics

The micromechanical approach aims to provide a comprehensive understanding of the damage mechanism at the macroscale. A random macrostructure is generated by computation from the known behaviour of microstructures, each microstructure being characterised by a finite number of parameters (Zaitsev, 1985). On the basis of micro- and macroscale relationships, Dang-van (1973) proposed a multiaxial fatigue criterion with a realistic physical interpretation of

fatigue phenomena. During a polycyclic fatigue test, the stress at the macroscopic scale remains elastic. However, at the microscopic scale, the metal is neither isotropic nor homogeneous. It is constituted of randomly oriented crystals. This induces local fluctuations of the microscopic stress and defines the macroscopic stress. Thus the local microscopic stress can locally exceed the yield strength in certain unfavourably oriented grains, whereas the macroscopic stress remains elastic. If the cyclic plastic response of the grain to the solicitation is not elastic shakedown, some microcracks will appear. These microcracks coalesce to form a crack of detectable size. This formulation has been recently extended by Papadopoulos (1987) and Deperrois (1991) for a better fitting with experimental results.

Nevertheless, the main question still remains: What is fatigue damage?

Several types of fatigue damage have been identified by Mughrabi et al. (1983) without leading to a practical quantitative characterisation:

- persistent slip bands (PSB) characterised by extrusion shape and height; roughness profile of extrusion; and microcracks formed (a) at the interfaces between PSB and matrix, and (b) in valleys of surface roughness of PSB surface profile;
- surface roughness originating from random reversible slip within PSB and in planar slip materials without PSB;
- fatigue damage at grain boundaries (GB) due to impinging PSB in the form of (a) slip step formation at GB, and PSB-GB cracks.

Many attempts have been made to measure local plastic strains within individual grains using:

- (1) thin mica flakes as reference gauges to determine surface displacements over 20 μm gauge lengths (James, 1983);
- (2) X-ray line-broadening studies and stress analyses to characterise quantitatively the fatigue-induced lattice deformation and change in the residual stress prior to crack initiation (Field, 1983);
- (3) small-angle neutron scattering (SANS) measurements to give void nucleation rates and individual void growth rates as functions of loading parameters (Cabañas, 1983);

(4) oxide films as quantitative sensors of metal fatigue (Baxter, 1983);

(5) decrease in load at constant strain amplitude chosen as damage parameter (Pluvinage, 1983);

(6) statistical analysis of small surface cracks randomly distributed over unnotched smooth surfaces that often initiate, grow and coalesce (Kitagawa, 1983);

(7) sliding-off process which is related to the crack tip opening displacement (McEvily, 1983);

(8) microhardness technique for determining the plastic zone dimensions, its form and contour and the distribution of plastic strain within it (Loye, 1983);

(9) plastic deformations measured by interferential contrast, interferometry and microhardness methods (Ranganathan, 1983).

The ASTM STP 811 meeting in 1982 concluded that fatigue damage can be defined as:

- a chemical–physical process whereby irreversible degradation of a specific property results from the application of cyclic stress and strain; or
- a physical separation of the material (cracks, cavitation, etc.).

More significant advances in understanding fatigue damage must make a clear distinction between: the physical damage, the process of damage and the manifestation of damage.

4. Heat production mechanism during fatigue process

Fatigue cracks in individual crystals are generally assumed to develop within glide bands. The reason for the start of a fatigue crack is the embrittlement of the material within the glide bands due to gradual exhaustion of potential slip planes under reversed stressing. A more specific mechanism (Freudenthal, 1956) of fatigue crack initiation within glide bands is the development of highly generated temperature and associated thermal stress gradients in the front of any active slip plane, resulting from the conversion into heat of the work in slip of the applied forces. The concept of temperature flash (Blok, 1954) accounting for crack initiation under repeated stressing provides

a tentative explanation for the observed thermal softening in fatigue of previously cold-worked metal. This seems to be consistent with the assumption that under repeated stressing, relatively high temperatures are developed within the glide bands. The distribution and the character of glide bands under conditions of relatively rapidly repeated stress cycles differ significantly from that produced by unidirectional stressing.

The localisation of slip under rapidly applied repeated stress cycles is explained by the consideration of the transiently viscous response of newly formed slip bands (Zener, 1948) which appear to be the result of transient disorder within the slipped region. Shear stresses in such bands are relieved almost immediately after their formation. Slip under partly or totally reversed rapidly applied repeated stress cycles is thus sharply concentrated within the region of initial slip by the same process of quasi-viscous stress relaxation along a newly formed slip band that causes outward spreading of slip in unidirectional stressing. The local temperature increase, on individual slip planes or within a cluster of slip planes, is high enough to produce, in the vicinity of the slip region, localised thermal stresses of the order of magnitude of the tensile strength of the metal. The development of localised high temperatures, in the course of sharply localised slip, might be considered a plausible mechanism of fatigue crack initiation.

In cases of unavoidable presence of small cracks and of structural inhomogeneities, the stress distribution is more or less inhomogeneous in the material. For a brittle material, fracture occurs when the stress at the stress concentration location reaches the yield value. If the material is ductile, it will yield at the points where local maxima of stress occur before the value of the strength is reached. Further increase of load causes more plastic strain at these points, but no considerable increase of the stress beyond the yield limit. Subsequently, if the load is alternating, the local plastic deformations will not come to an end, but will alternate and thus produce a progressive strain hardening of the material situated at the stress peaks. Consequently, the stress at which plastic yielding begins will rise in the course

of the load fluctuations, the smoothing out of the stress distribution becomes less and less effective, and the maximum stress at the stress peaks rises until finally a crack may be formed if at a point the local stress reaches the strength value. This may be the reason why a load which is harmless under static conditions can cause fracture if applied repeatedly (Orowan, 1938).

Since the fatigue phenomenon is generally caused by the cyclic plastic strain (Feltner, 1961), the plastic strain energy plays an important role in the damage process (Morrow, 1965). Fatigue cracks generally initiate from surface defects or discontinuities and are thus predominantly influenced by the surface stress system. The significance of such an energy approach is in its ability to unify microscopic and macroscopic test data, and subsequently to facilitate the detection of the manifestation of damage. Therefore, the idea of relating fatigue to intrinsic dissipation seems to be highly relevant. Using the framework of thermodynamics of irreversible processes, Bui and Stolz (1987) assume that the intrinsic dissipation yields the constitutive equations of the material and then suggest measurements of temperature rise due to loading.

According to Moore and Kommers (1921), the temperature test was suggested and to some extent used by C.E. Stromeyer of Manchester, UK as long ago as 1913. However, in their research for a rapid test for predicting fatigue resistance, their technique, based on the use of thermocouples, did not permit to establish accurately the temperature limit as the same as the endurance limit under repeated stress. Recently several researchers have encountered similar difficulties in measuring dissipated energy (Galtier, 1993; Gomma, 1980). Gross (1981) developed a calorimetric technique for measuring the heat evolved per cycle. The temperature gradient was measured with thermistors cemented to the sample with conducting paste. In practice, the specimen was stress cycled until a constant temperature gradient was reached, and then the decay of the temperature gradient was measured, after ceasing the cycling.

The question of when does a crack initiate to become a propagating crack, seems to be some-

what philosophical, particularly when searching for a rapid test for predicting fatigue resistance. This is found by using the infrared thermographic technique to quantitatively evaluate the rise of temperature under a reversed stress applied for a few minutes or less. Infrared thermography readily detects the occurrence of both initiation and propagation of failure. It may be used to establish allowable stress levels and inspection requirements so that fractures cannot occur. In addition, this technique describes the failure location and process of the structure failure.

Infrared thermography has been successfully used as an experimental method to detect the plastic deformation of a steel plate under monotonic loading (Bui, 1981) or as a laboratory technique for investigating damage, fatigue and failure mechanisms occurring in engineering materials (Luong, 1990). Based on the fact that plastic deformation is not homogeneous, the stress acting upon a plastic inhomogeneity that is embedded in elastic surroundings is a function of its plastic strain, diminishing with increasing strain. Even without any external strain being produced, and/or flaw coalescence when increasing irreversible micro-cracking is induced by fatigue loading, the generated plastic dissipation is detected in this study by infrared thermography owing to the thermomechanical coupling.

5. Infrared thermography background

Traditionally, the thermomechanical coupling effects have been neglected in thermal analyses. The inelastic deformation is generally assumed rate (time) independent at low homologous temperatures. The theory of plasticity is consequently formulated in a rate (time) independent fashion and phenomena such as loading rate sensitivity, creep and relaxation are excluded. The temperature field and the deformation induced by the thermal dilation and mechanical loads were solved separately. However, this effect could become noticeable if the material is significantly loaded beyond its reversible threshold.

The development of the thermo-visco-elastic-plasticity equations requires three types of basic

assumption (Allen, 1985; Dillon, 1963; Kratochvil, 1969; Taylor, 1925).

• The basic thermomechanical quantities describing thermodynamic processes: the motion x , the second Piola–Kirchhoff stress tensor S , the body force per unit mass b , the Helmholtz free energy ψ , the specific entropy s , the heat supply r , the absolute temperature T , the heat flux vector per unit area q , the elastic strain tensor E^e , the inelastic strain tensor E^I and a set of internal state variables $\alpha^{(i)}$ characterising the material.

• The fundamental equations of mechanics postulating for the balance laws of linear momentum, angular momentum, and energy, as well as the second law of thermodynamics expressed in the variables given above.

(1) Balance of linear momentum

$$\nabla S F^T + \rho(b - \ddot{x}) = 0 \quad (1)$$

where F denotes the transformation gradient. The conservation of angular momentum is expressed by the symmetry of the stress tensor.

(2) Balance of energy

$$\rho(\dot{\psi} + s\dot{T} + s\dot{T}) = \rho\dot{e} = S : \dot{E} - \text{div } q + \rho r \quad (2)$$

The balance laws are assumed not to change from those in thermoelasticity. This postulate leads to the use of the internal state variable type thermodynamics (Kratochvil, 1969).

(3) Second law of thermodynamics expressing the entropy production inequality:

$$-\rho(\dot{\psi} + s\dot{T}) + S : \dot{E} - q \frac{\nabla T}{T} \geq 0 \quad (3)$$

where ρ (kg m^{-3}) is the mass unit in the reference configuration, e is the specific internal energy and E is the Green–Lagrange strain tensor given by $E = (\nabla x^T \cdot \nabla x - 1)/2$. The superposed dot stands for the material time derivative. The continuity equation and the balance of angular momentum are implicitly satisfied in the fundamental equations.

• The constitutive assumptions describing the material response and assuring the compatibility of the constitutive equations with the fundamental equations of mechanics. When adopting the separability of the strain tensor

$$E = E^e + E^I + \beta(T - T_R) \quad (4)$$

where β is the coefficient of the thermal expansion matrix and T_R the reference temperature. The requirement of the second law of thermodynamics yields:

- (1) the response functions S , ψ and s are independent of the temperature gradient ∇T ;
- (2) ψ determines both the stress tensor and the specific entropy through

$$S = \rho \frac{\partial \psi}{\partial E^e}$$

and

$$s = -\frac{\partial \psi}{\partial T} + \frac{\partial \psi}{\partial E^e} : \beta$$

(3) ψ , \dot{E}^I and q obey the general inequality

$$\left(S - \rho \frac{\partial \psi}{\partial E^I} \right) : \dot{E}^I - q \frac{\nabla T}{T} \geq 0 \quad (5)$$

The above thermodynamic restrictions may now be applied to equation of energy conservation, yielding:

$$\rho \left(\frac{\partial \psi}{\partial E^I} - T \frac{\partial^2 \psi}{\partial T \partial E^I} \right) : \dot{E}^I - T \frac{\partial S}{\partial T} : \dot{E}^e - \rho T \frac{\partial^2 \psi}{\partial T^2} \dot{T} + \dot{S} \beta T = S : \dot{E}^I - \text{div } q + \rho r \quad (6)$$

Assuming

$$\psi = \psi_0 + (E^e : \overset{4}{D} : E^e)/2 - C_v T \ln \left(\frac{T}{T_R} - 1 \right) \quad (7)$$

and the Fourier heat conduction law

$$q = -K \text{ grad } T \quad (8)$$

This leads to the coupled thermomechanical equation:

$$\rho C_v \dot{T} = \rho r + K \nabla^2 T - (\beta : \overset{4}{D} : \dot{E}^e) T + S : \dot{E}^I \quad (9)$$

where β denotes the coefficient of the thermal expansion matrix, C_v ($\text{J kg}^{-1} \text{K}^{-1}$) is the specific heat at constant deformation, $\overset{4}{D}$ is the fourth-order elasticity tensor, e is the specific internal energy, K ($\text{W m}^{-1} \text{K}^{-1}$) is the thermal conductivity, and T is the absolute temperature.

The volumetric heat capacity $C = \rho C_v$ of the material is the energy required to raise the temperature of unit volume by 1 °C (or 1 K).

This equation defines the potential applications and various uses of the infrared scanning technique in engineering problems. However the detected temperature rise, resulting from four quite different phenomena, must be correctly discriminated by particular test conditions and/or specific data reduction. This is the main difficulty when interpreting the thermal images obtained from experiments under usual conditions.

5.1. Heat sources

The first term is related to the existence of sources or sinks of heat in the scanning field (Cielo, 1987). The surface heat patterns displayed on the scanned specimen may be established either by external heating, referred to in the literature as passive heating where local differences in thermal conductivity cause variations on isothermal patterns, or by internally generated heat referred to as active heating (Reifsnider, 1980). In the following reported experiments, thermal noise generated by gripping systems may sometimes obscure the intrinsic dissipation of the tested specimen.

5.2. Thermal conduction

The second term on the right hand side of the coupled thermomechanical equation governs the transference of heat by thermal conduction in which the heat passes through the material to make the temperature uniform in the specimen. The second order tensorial nature of the thermal conductivity K may sometimes be used for the detection of anisotropy of heavily loaded materials. The variances in thermal conductivity may arise because of local inhomogeneities or flaws in the material (McLaughlin, 1987). Where an unsteady state exists, the thermal behaviour is governed not only by its thermal conductivity but also by its heat capacity. The ratio of these two properties is termed the thermal diffusivity $\alpha = K/C$ which becomes the governing parameter in such a state. A high value of the thermal diffusivity

implies a capability for rapid and considerable changes in temperature. It is important to bear in mind that two materials may have very dissimilar thermal conductivities but, at the same time, they may have very similar diffusivities. A pulsed heat flux has been used to characterise a delamination in a composite by the break caused in the temperature time history (Balageas, 1987).

5.3. Thermoelasticity

The third term illustrates the thermoelastic coupling effect. Within the elastic range and when subjected to tensile or compressive stresses, a material experiences a reversible conversion between mechanical and thermal energy causing it to change temperature. Provided adiabatic conditions are maintained, the relationship between the change in the sum of the principal stresses and the corresponding change in temperature is linear and independent of loading frequency. It is the reversible portion of the mechanical energy generated; this thermoelastic coupling term may be significant in cases of isentropic loadings. A stress analysis technique is known as SPATE (stress pattern analysis by thermal emissions) that measures the temperature due to the thermoelastic heating and cooling of a body under cyclic loading (Oliver, 1986).

5.4. Intrinsic dissipation

The last term defines the energy dissipation generated by viscosity and/or plasticity. Internal energy dissipation was recognised by many scientists. The work done on the system by plastic deformation is identified as the major contribution to heat effect. In thermo-elastic-plasticity, there exists a general acceptance that not all the mechanical work produced by the plastic deformation can be converted to the thermal energy in the solid. A portion of the work is believed to have been spent in the change of material microscopic structure as shown in Table 1. The work done in plastic deformation per unit volume can be evaluated by integrating the material stress-strain curve. This internal dissipation term constitutes a significant part of the non linear coupled

Table 1
Thermo-elastic-plastic couplings

Postulations and internal variables (IV)	Stored energy at microlevel	Internal energy dissipation rate D	Heat to plasticity
Dillon (1963) IV, ϵ_{ij}^p responsible for D	0	$\sigma_{ij}\dot{\epsilon}_{ij}^p = \sigma'_{ij}\dot{\epsilon}'_{ij}$	0
Lee (1969), IV = plastic power $\sigma_{ij}\dot{\epsilon}_{ij}^p$	$(1 - \gamma)\sigma_{ij}\dot{\epsilon}_{ij}^p$ ($0.9 \leq \gamma \leq 1.0$)	$\gamma\sigma_{ij}\dot{\epsilon}_{ij}^p$	0
Nied and Batterman (1972) IV = ω , χ = dislocation energy, $\dot{\chi} = \sigma_{ij}\dot{\epsilon}_{ij}^p$	$\Lambda\sigma_{ij}\dot{\epsilon}_{ij}^p$ $\Lambda = \frac{\text{stored energy}}{\text{expended inelastic energy}}$	$(1 - \Lambda)\sigma_{ij}\dot{\epsilon}_{ij}^p$	$T\chi\frac{\partial\Lambda}{\partial\chi}$
Raniecki and Sawczuk (1975), IV = work hardening κ , ω = integrating factor, $\dot{\kappa} = \omega(\sigma_{ij}, T)\sigma_{ij}\dot{\epsilon}_{ij}^p$	$\chi(\kappa, T)\dot{\kappa}$	$\sigma_{ij}\dot{\epsilon}_{ij}^p - \pi\dot{\kappa}$ $\pi = \text{IV conjugate}$	$T\frac{\partial\pi}{\partial T}$
Mroz and Raniecki (1976), IV = κ , $\dot{\kappa} = \sigma'_{ij}\dot{\epsilon}_{ij}^p$	$\pi = -\frac{\partial D}{\partial\dot{\kappa}}$	$\sigma_{ij}\dot{\epsilon}_{ij}^p - \pi\dot{\kappa}$	$T\frac{\partial\pi}{\partial T} = 0$
Lehman (1979) IV = K , $\dot{\zeta}$ = experimental constant, $\dot{K} = (1 - \zeta)\sigma_{ij}\dot{\epsilon}_{ij}^p$	$\dot{K} = (1 - \zeta)\sigma_{ij}\dot{\epsilon}_{ij}^p$	$\zeta\sigma_{ij}\dot{\epsilon}_{ij}^p$	0

thermomechanical analysis. The quantification of this intrinsic dissipation for engineering materials is an extremely difficult task without infrared thermography (Chrysochoos, 1992). The infrared thermographic technique is mainly concerned with differences in temperature (or thermal gradients) that exist in the material rather than with the absolute value of temperature.

Ignoring the significance of the coupled thermomechanical equation, an attempt has been made without success by Leaity and Smith (1989) to monitor thermoemissions during fatigue crack propagation tests. The SPATE technique used was unable to detect the changes in thermoemission caused by small and slow crack tip advances.

The work, reported in this paper, considers the intrinsic dissipation as the most accurate indicator of damage manifestation. It highlights the advantages of the infrared thermographic technique, used for the detection and the discrimination of this non linear coupled thermomechanical effect

within the framework of a consistent theoretical background.

6. Short-time evaluation of fatigue limit

Infrared thermography is a convenient technique for producing heat images from the invisible radiant energy emitted from stationary or moving objects at any distance and without surface contact or in any way influencing the actual surface temperature of the objects viewed. The temperature rise ahead of a fatigue crack has been measured using an AGA thermovision camera (Attermo, 1971) in order to demonstrate the local heating at the tip predicted by Barenblatt et al. (1968). Attempts have been made to measure and characterise the heat generated during the cyclic straining of composite materials (Reifsnider, 1974). The scanning infrared camera has been used to visualise the surface-temperature field on

steel and fiberglass–epoxy composite samples during fatigue tests (Charles, 1975).

6.1. Infrared scanner

For this work, a scanning camera is used which is analogous to a television camera. It utilises an infrared detector in a sophisticated electronics system in order to detect radiated energy and to convert it into a detailed real-time thermal image in a colour and monochrome video system. Response times are shorter than 1 μ s. Temperature differences in the heat patterns are discernible instantly and represented by several distinct hues.

The quantity of energy W ($W\ m^{-2}\ \mu m^{-1}$), emitted as infrared radiation, is a function of the temperature and emissivity of the specimen. The higher the temperature, the more important the emitted energy. Differences of radiated energy correspond to differences of temperature.

The AGA 782 SW infrared scanner unit employed (AGA, 1984) comprises:

- a set of infrared lens which focuses the electromagnetic energy, radiating from the object being scanned, into the vertical prism;
- an electro-optical mechanism which discriminates the field of view in 10^4 pixels by means of two rotating vertical ($180\ rev\ min^{-1}$) and horizontal ($18\ 000\ rev\ min^{-1}$) prisms with a scanning rate of 25 fields s^{-1} ;
- a set of relay optics containing a selectable aperture unit and a filter cassette unit which focuses the output from the horizontal prism onto a single element point detector, located in the wall of a Dewar chamber;
- a photovoltaic SW short waves infrared detector composed of indium antimonide (InSb) which produces an electronic signal output varying in proportion to the radiation from the object within the spectral response 3.5 to 5.6 μm ;
- a liquid nitrogen Dewar which maintains the InSb detector at a temperature of $-196\ ^\circ C$ allowing a very short response time of about 1 μ s; and
- a control electronics with preamplifier which produces a video signal on the display screen.

Since the received radiation has a non linear relationship to the object temperature, and can be affected by atmosphere damping and includes

reflected radiation from the objects' surroundings, calibration and correction procedures have to be applied. Knowing the temperature of the reference, the object temperature can then be calculated with a sensitivity of 0.1 $^\circ C$ at 20 $^\circ C$. The infrared scanner unit converts electromagnetic thermal energy radiated from the tested specimen into electronic video signals. These signals are amplified and transmitted via an interconnecting cable to a display monitor where the signals are further amplified and the resultant image is displayed on the screen.

6.2. Rotating bending testing

The material for the rotating bending tests was an XC55 steel, used quite extensively in automobile construction. To minimise scatter, the 6.74 mm diameter specimens have been prepared from a single melt. The number of load cycles was 10^7 corresponding to the automobile fatigue damage. Cyclic fatigue tests were performed on a four-point loading rotating bending Schenck machine (Fig. 1) running at approximately 100 Hz.

A total of 18 specimens was step-tested according to the staircase or up-and-down method, meaning that each specimen was run for 10^7 cycles at 370 MPa, whereupon the stress was raised in 10 MPa step if there is nonfailure and the stress is lowered in case of failure. Using standard methods of statistical analysis, the fatigue limit has been estimated equal to 399 MPa with a standard deviation of 41 MPa (Fig. 2).

A series of five rotating bending tests has been scanned by the infrared system at different stress levels that must be chosen in accordance with the step-by-step procedures for using statistical methods in usual fatigue testing. All specimens were coated with matt black spray paint to maximise their emissivity. The paint coating raises the surface emissivity to a uniform high level. In addition it allows examination of the surface undertaken at oblique angles to the surface without degradation of sensitivity. Also the recommended paint coating will reduce surface reflections and will ensure uniformity of response across the specimen. With a loading frequency of 100 Hz and after stabilisation of the temperature rise, the load duration

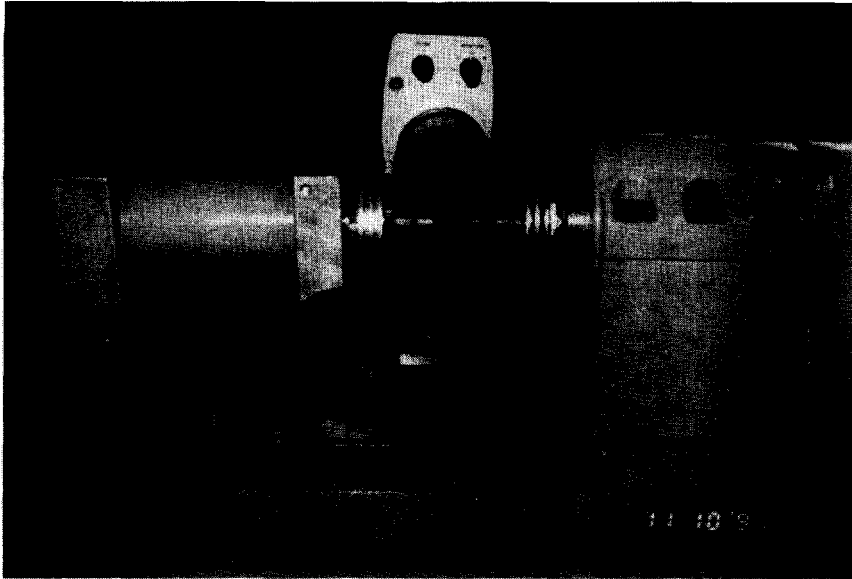


Fig. 1. Steel specimen subjected to rotating bending.

chosen was 30 s and 60 s corresponding respectively to 3000 load cycles and 6000 load cycles (Fig. 3).

The Agema SW-782 infrared scanner, incorporating a high-temperature filter and equipped with a real-time system Discon (digital infrared system for coloration) converting thermal images into a ten-colour isotherm display, was used to record the bulk of the heat emission data. That device displays a ten-colour calibrated surface-temperature picture of the specimen. Each colour hue corresponds to 0.2 °C.

Apparently the gripping system on the left side (Fig. 3) generated undesirable heat that tended to obscure the intrinsic dissipation of the loaded specimen. Fortunately in this case, the variation of intrinsic dissipation during 30 s or 60 s was much larger than the change of gripping phenomena. In accordance with the coupled thermomechanical equation, the analysis of thermal images has been performed by isolating the intrinsic dissipation from thermal noises by simply subtracting the thermal image at reference time from the thermal image at 3000 cycles or 6000 cycles. A computer aided thermography software TIC 8000 allowed the data reduction of the thermal images using the function subtraction of images. The resulting image is a subtracted image showing the temperature difference between the two compared images at reference time and at 30 s or 60 s. These thermal images provided quantitative values of intrinsic dissipation of a steel specimen in rotating bending under 370 MPa caused by 3000 and 6000 load cycles (Fig. 4). The same analysis procedure has been applied for each load step.

The manifestation of the fatigue damage mechanism is revealed by a break of the intrinsic dissipation regime of the loaded specimen. Experimental results are summarised in Fig. 5 which

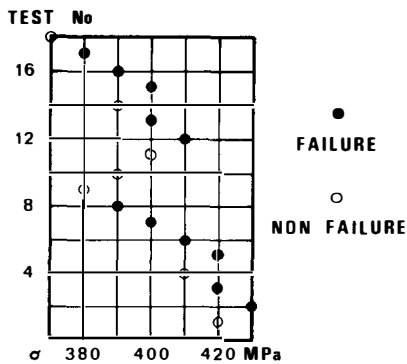


Fig. 2. Standard staircase determination of fatigue limit.

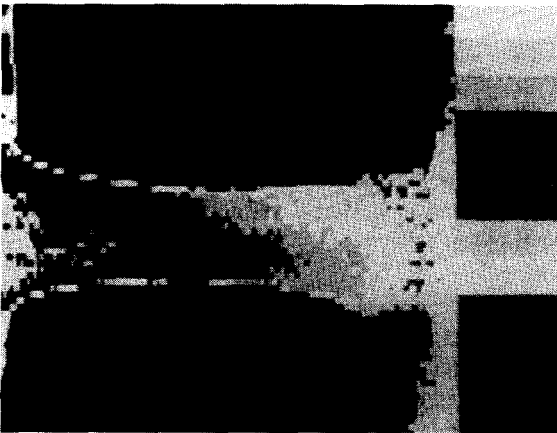
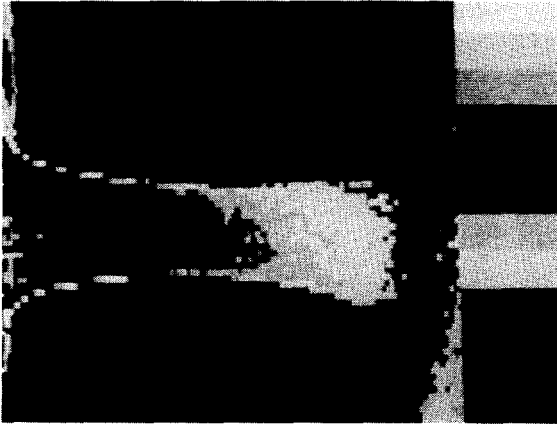


Fig. 3. Thermograms of a steel specimen under 360 MPa after 3000 and 6000 load cycles.

illustrates how the fatigue limit is determined using a graphical procedure. The threshold of critical thermal dissipation is roughly the same for the 3000 cycles (filled squares) and 6000 cycles (open circles) curve. It corresponds to the value deduced from standard procedure (Fig. 2). The star point at co-ordinates (600 MPa, 180 °C) represents the last load step where failure occurs. These experiments have shown that the infrared thermographic technique can provide the fatigue limit of XC55 steel within a few hours instead of several months when using the standard staircase method.

The described experimental procedure has readily been extended to the fatigue resistance evaluation of automotive components such as a

connecting rod subjected to cyclic tension fatigue testing (Fig. 6).

A graphical determination, deduced from experimental results obtained on one specimen, has given the fatigue limit within 2 h (Fig. 7). The reduction in fatigue time determination by infrared thermographic technique is really very significant!

Recently we have successfully applied this one specimen method to quantitative measurement of

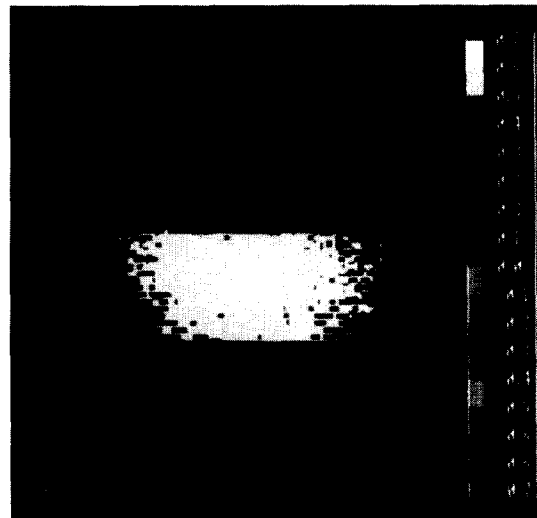
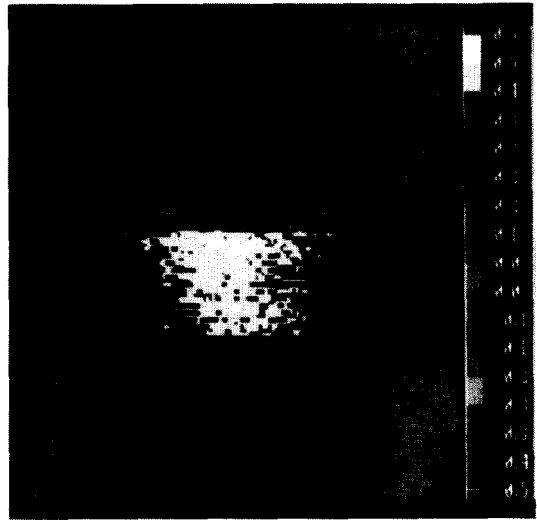


Fig. 4. Intrinsic dissipation of a steel specimen.

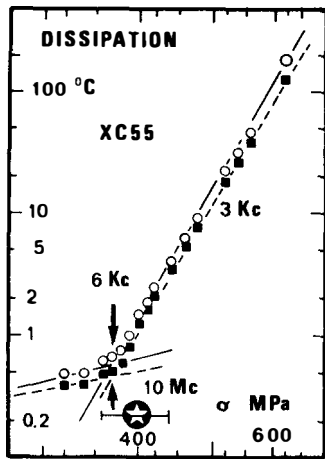


Fig. 5. Graphical determination of the fatigue limit of a steel specimen.

fatigue testing for steel, cast iron, micro-alloyed steel specimen with polished or rough surface under tension-compression, plane bending and torsion loadings.

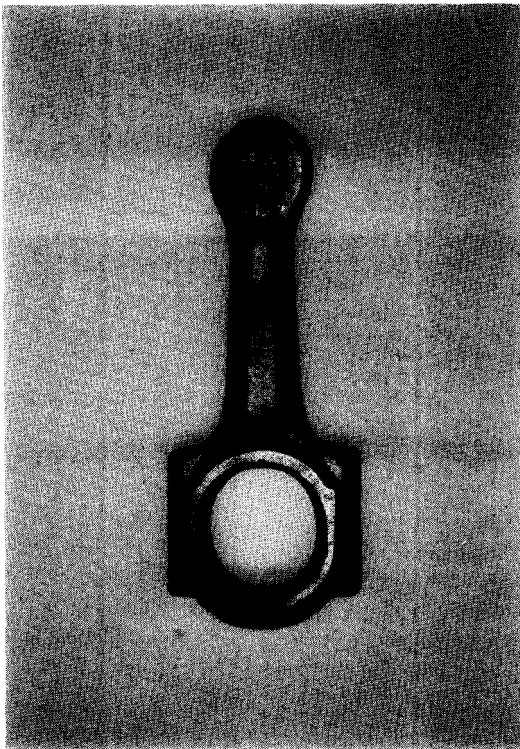


Fig. 6. Connecting rod specimen under cyclic tensions.

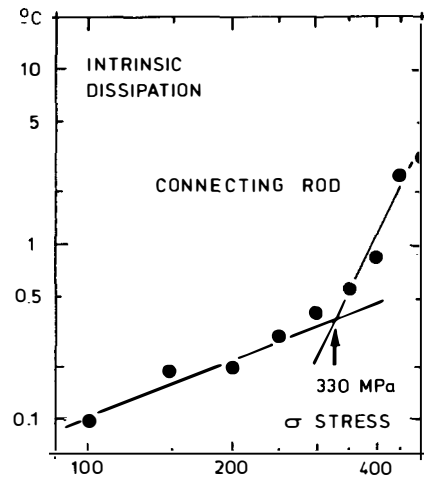


Fig. 7. Graphical determination of the fatigue limit of a connecting rod.

7. Concluding remarks

This work has demonstrated that the dissipativity of the tested materials under fatigue loading is the most sensitive and accurate manifestation of damage.

Owing to the thermomechanical coupling, infrared thermography provides a non destructive, non contact and real-time test to observe the physical process of metal degradation and to detect the occurrence of intrinsic dissipation. Thus it readily gives a measure of the material damage and permits to evaluate the limit of a progressive damaging process under load beyond which the material is susceptible to failure. Detecting a strong change of intrinsic dissipation regime, this method readily allows a rapid evaluation of the endurance limit, commonly determined by a very time-consuming procedure.

It is of particular interest that the method allows not only qualitative work such as finding flaws, but also quantitative analysis of the effects of flaws on strength and durability of structural components. This useful and promising technique offers accurate illustration of crack initiation, the onset of its unstable propagation through the material and/or flaw coalescence when increasing irreversible micro-cracking is generated by cyclic loading. Particularly in the case of fatigue testing, the infrared thermographic technique evidences

the initiation of a crack and its propagation through the material. The main interest of this energy approach is to unify microscopic and macroscopic test data. Subsequently it may suggest multiaxial design criteria, highly relevant for full-scale testing on engineering structures.

Infrared thermography is an attractive and relatively unexplored technique for the non destructive evaluation of fatigue limit in industrial materials and structures. The main advantages of this technique are speed and non contact operation. Signal processing techniques have been efficiently used to extract more quantitative information. Significant developments are expected in the near future, capitalising on the recent progress in computing power and image-processing techniques. The opportunities offered by thermal techniques in terms of remote operation and fast surface-scanning rates are particularly attractive for on-line applications.

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