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NONDESTRUCTIVE EVALUATION OF FATIGUE LIMIT OF METALS USING INFRARED THERMOGRAPHY

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ABSTRACT

The paper aims to illustrate three advantages of infrared thermography as a non-destructive, real-time and non-contact technique. It permits first observation of the macrostructural aspects of thermoplasticity describing damage and failure processes in metals, and in particular, automotive components subjected to fatigue loading, second detection of the occurrence of intrinsic dissipation, and third evaluation of the fatigue strength in a very short time, compared to traditional fatigue testing techniques. In addition, infrared thermography readily describes the damage location and the evolution of structural failure.

INTRODUCTION

Fracture mechanics has become the primary approach to controlling brittle fracture and fatigue failure in structures. Fracture process is an energy-consuming phenomenon. The thermal effect due to thermomechanical coupling at the tip of a moving crack has been investigated [5] within the framework of thermodynamics, taking into account stress and strain singularities.

Internal energy dissipation was recognised by well-known scientists [16-17-25-27-28-29]. Carrying out experiments on the cyclic twisting of cylindrical bars, Dillon [10] identified the work done to the system by plastic deformation as the major contribution to the heat effect and proposed an internal dissipation rate $D = \sigma_{ij} \dot{\epsilon}_{ij}^p = \sigma_{ij} \dot{\epsilon}_{ij}^p$ where σ_{ij} is the stress, $\dot{\epsilon}_{ij}^p$ is the rate of the plastic strain, σ_{ij} and $\dot{\epsilon}_{ij}^p$ are the respective deviatoric stress and strain rate components. Well-developed empirical theories of plastic deformation in metal allowed engineers successfully to predict the behaviour of a variety of structures and machine elements loaded beyond the elastic limit for purposes of design.

This paper emphasises the application of infrared thermography to detect the macrostructural aspects of thermoplasticity describing the occurrence of damage and fatigue processes in metals. The proposed infrared thermographic technique is subsequently used to evaluate the fatigue limit in a very short time, defined as a drastic change in the rate of intrinsic dissipation.

HEAT PRODUCTION MECHANISM

Since fatigue is generally caused by cyclic plastic strain, the plastic strain energy plays a very significant role in the damage process [11-13-22-23]. The significance of such an energy approach is in its ability to unify microscopic and macroscopic testing data. Therefore, the idea of relating fatigue to the intrinsic dissipation detected by infrared thermography seems to be highly relevant.

Metal fatigue of aircraft components was detected very early in the history of powered flight [19], and it was also of major importance in determining the durability of ground vehicles. The failure mode was identified early by railway engineers. Even very low failure rates can produce an appreciable number of failures [20]. Fatigue phenomena, leading for example to the failure of diesel engines [12], were poorly understood until recently because they occur unexpectedly at relatively low stress levels. Some progress has been made recently in design methods [3].

Damage theories rely on assumed discontinuous phenomena at the microscopic scale [6]. Damage parameters, considered as internal variables, are introduced at the macroscopic scale. Kachanov [14] introduced a continuous variable D , related to the scalar density of defects. Taking into account the most fundamental aspects of inelastic deformation and neglecting the details at the microstructural level, Mroz [24] suggested phenomenological constitutive models for engineering applications. On the basis of micro- and macro-scale relationships, Dang-van [8] 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 is not an elastic shakedown, then some microcracks will be nucleated. They could coalesce to form a crack of detectable size. This formulation has been recently extended for a better fitting with experimental results [9].

Despite this wealth of methods developed by engineers over the years, the principal question that remains unanswered is: what is the physical phenomenon called fatigue damage? The ASTM STP 811 meeting in 1982 on fatigue mechanisms (advances in quantitative measurement of physical damage concluded that fatigue damage can be defined as: i) a chemical-physical process whereby irreversible degradation of a specific property results from the application of cyclic stress and strain, or ii) a physical separation of the material (cracks, cavitation, etc.). Understanding fatigue damage requires making a clear distinction between the physical damage, the process of damage, and the *manifestation of damage*. Various heat production mechanisms have been proposed by various authors and are now discussed. According to Moore and Kommers [21], the temperature test was suggested and to some extent used by C.E. Stromeyer of Manchester in England as early as 1913. However, their search for some short-time test to predict fatigue resistance, based on the use of thermocouples was not conclusive since they could not identify a critical temperature with the endurance limit of steel specimens subjected to cyclic loading.

This paper proposes using differential infrared thermography to quantitatively evaluate the *evolution of temperature* generated by the specimen under reversed stresses applied for a few minutes or less. Infrared thermography has been successfully used as an experimental method to detect the plastic deformation of a steel plate under monotonic loading [4], or as a laboratory technique for investigating damage, fatigue, and failure mechanisms occurring in engineering materials [18]. Plastic deformation is not homogeneous and the stress acting on a plastic inhomogeneity embedded in an elastic surrounding is a function of its plastic strain, diminishing with increasing strain. Due to the thermomechanical coupling, the generated plastic dissipation is readily detected by infrared thermography.

INFRARED THERMOGRAPHY BACKGROUND

The development of the thermo-elastic-plasticity equations [1-10-15-29] leads to the following coupled thermomechanical equation:

$$\rho C_v \dot{T} = r_0 + K \nabla^2 T - \left(\beta : D : \dot{E}^e \right) T + S : \dot{E}^I$$

where β denotes the coefficient of the thermal expansion matrix, r_0 the heat supply, E^e the elastic strain tensor, E^I the inelastic strain tensor, C_v the specific heat at constant deformation, D the fourth-order elasticity tensor, e the specific internal energy, K the thermal conductivity, and finally T the absolute temperature. This equation shows the potential applications of the infrared scanning technique in diverse engineering domains (detection of fluid leakage, non-destructive testing using thermal conduction phenomena, elastic stress measurements, and localisation of dissipative phenomena). Thus the detected temperature change, 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 the usual conditions.

The last term on the right-hand side of the thermomechanical equation defines the energy dissipation due to plasticity and/or viscosity. A significant contribution of the work by plastic deformation is converted into heat. The work done by plastic deformation per unit volume can be evaluated by integrating the material stress-strain curve. Infrared thermography readily detects the internal dissipation term, which constitutes an important part of the non-linear coupled thermomechanical analysis. The proposed thermographic technique is mainly concerned with the

differences in temperature (or thermal gradients) that exist in the material rather than with the absolute values of temperature. It conveniently detects the *dissipation evolution* of the material under loading. The reported work considers 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 physical phenomena involved in this non-linear coupled thermomechanical effect.

SHORT-TIME EVALUATION OF FATIGUE LIMIT

Infrared thermography is a convenient technique for producing heat pictures from the invisible radiant energy emitted from stationary or moving objects at any distance and without surface contact or any perturbation of the actual surface temperature of the objects viewed. The temperature rise ahead of a fatigue crack has been measured and thus proved using an AGA thermovision camera by Attermo & Ostberg [2]. Attempts to measure and characterise the heat generated during the cyclic straining of composite materials have also been made [7] during fatigue tests.

A scanning camera, analogous to a television camera, utilises an infrared detector in a sophisticated electronics system. It detects radiated energy and converts it into a detailed real-time thermal picture in a video system either in colour or monochromatically. Response times are shorter than one microsecond. Temperature differences in the heat patterns are discernible instantly and are represented by several hues. The quantity of energy W 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 in use comprises:

- A set of infrared lenses 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 rpm) and horizontal (18,000 rpm) prisms with a scanning rate of 25 fields per second,
- 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-wave 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 $3.5 \mu\text{m}$ to $5.6 \mu\text{m}$,
- A liquid nitrogen Dewar which maintains the InSb detector at a temperature of $-196 \text{ }^\circ\text{C}$ allowing a very short response time of about one microsecond, and
- An electronic control with preamplifier that produces a video signal on the display screen.

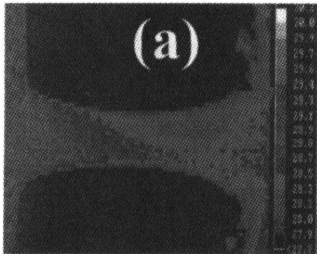
The received radiation has a non-linear relation with the object temperature, can be affected by atmosphere damping, and includes reflected radiation from the object's surrounding. In consequence, calibration and correction procedures have to be applied. Knowing the temperature of the reference, the view-field temperature can then be calculated with a sensitivity of $0.1 \text{ }^\circ\text{C}$ at $20 \text{ }^\circ\text{C}$. This infrared device is used to scan the following two fatigue test programs.

ROTATING BENDING TESTS

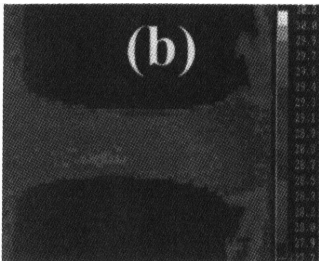
The material for the rotating bending tests was XC55 steel, quite extensively used in automobile construction. To minimise scatter, the 6.74 mm in diameter specimens have been prepared from a single melt. The number of load cycles was 10^7 corresponding to the automobile fatigue damage. Cyclic fatigue tests were performed on a 4-point loading rotating bending Schenck machine running at approximately 100 Hz. A total of 18 specimens was step-tested according to the Staircase or Up-and-Down method. This procedure means that each specimen was run for 10^7 cycles at 370 MPa for example, whereupon the stress was raised in 10 MPa steps for a comparable procedure in the absence of failure and the stress was lowered otherwise. Using standard methods of statistical analysis, the fatigue limit has been estimated to be equal to 399 MPa with a standard deviation of 41 MPa.

A series of five rotating bending tests have 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 matte 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 which is undertaken at oblique angles, without degradation of sensitivity. The recommended paint coating will also 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 chosen was 30 seconds and 60 seconds corresponding to 3,000 load cycles and 6,000 load cycles respectively.

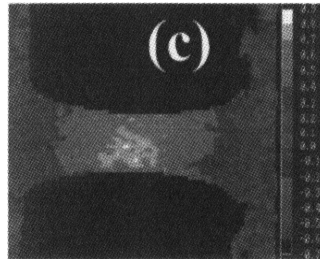
The AGEMA SW-782 infrared scanner, incorporating a high-temperature filter and equipped with a real-time system DISCON (digital infrared system for coloration) converting thermal images into a ten-colour isotherm display, was used to record the bulk of the heat emission data. That device displays a ten-colour calibrated surface-temperature picture of the specimen. Each colour hue corresponds to 0.2 °C. A computer-aided thermography software TIC 8000 allowed the data reduction of the thermal images that shows heat generation after 3,000 and 6,000 load cycles (Figure 1). These thermal images provided, by image subtraction $(b) - (a) = (c)$, quantitative values of the intrinsic dissipation of a steel specimen in rotating bending caused by 3,000 and 6,000 load cycles. The same 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 have been summarised in Figure 2 where it can be seen how the fatigue limit is determined using a graphical procedure. The threshold of critical thermal dissipation is roughly the same for the 3,000 cycles and 6,000 cycles curves, and it corresponds to the value deduced from standard procedure. The star point at coordinates (600 MPa, 180 °C) represents the last load step at which failure occurred. These experiments have shown that infrared thermography can provide the fatigue limit of XC55 steel within a few hours instead of the several months required when using the standard staircase method.



Thermal image at reference time



Thermal image after 3000 load cycles



INTRINSIC DISSIPATION
3000 load cycles at 380 MPa

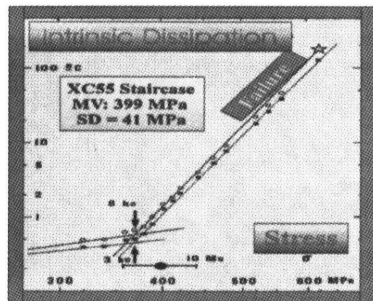


Figure 2 - Graphical determination of the fatigue limit of a XC55 steel.

Figure 1 - Intrinsic dissipation after 3,000 load cycles under 380 MPa (Temperature scale is given in °C).

TENSION-COMPRESSION TESTS ON CONNECTING RODS

Five tension-compression tests on connecting rods, prepared from a single melt and subject to a stress ratio $R = \sigma_{\max}/\sigma_{\min} = -2$, have been scanned by the infrared system at different stress levels in accordance with the step-by-step procedure as specified in the previous section. All connecting rod specimens were also coated with matte spray paint to maximise their emissivity. The testing procedure was similar to the one for the rotating bending case with cylindrical specimens. With a loading frequency of 20 Hz and after stabilisation of the temperature, the load duration chosen was 100 seconds corresponding respectively to 2,000 load cycles. The thermal images (Figure 3), processed by TIC 8000, provided quantitative values of the intrinsic dissipation of the connecting rods causing by 2,000 load cycles. The same procedure has been applied for each load step. The same thermal phenomenon as for the previous case of rotating bending was detected. Experimental results have been summarised in Figure 4 where it can be seen how the fatigue limit is determined using a graphical procedure. The threshold of critical thermal dissipation corresponds to the value deduced from standard procedure. These experiments have shown that infrared thermography can provide the fatigue limit of connecting rods within a few hours instead of several months when using the standard staircase method. Subsequently several other different fatigue test programs have been performed.

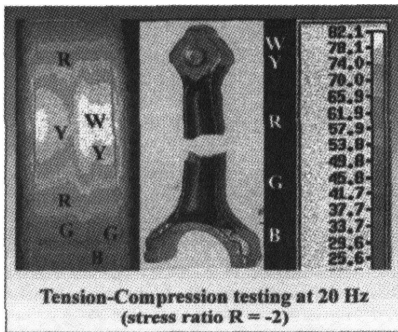


Figure 3 - Intrinsic dissipation of the connecting rod after 2,000 load cycles (Temperature scale is given in °C).

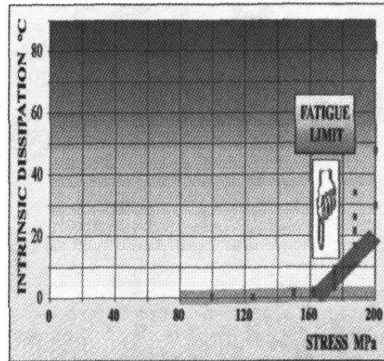


Figure 4 - Graphical determination of fatigue limit of a connecting rod.

CONCLUDING REMARKS

This work has demonstrated that the material dissipativity under fatigue loading is the highly sensitive and accurate manifestation of damage. Owing to the thermomechanical coupling, infrared thermography provides a non-destructive real-time test with no contact to observe the physical processes of metal degradation and to detect the occurrence of intrinsic dissipation. Thus, it readily provides a measure of the material damage and permits evaluation of the sharp limit of a low accumulation of damage beyond which the material leads quickly to failure. The paper illustrates the use of quantitative infrared thermography as a non-destructive and non-contact technique to detect the manifestation of the physical process of fatigue, and to evaluate rapidly in a few hours the fatigue limit of automotive components. The proposed technique has been applied successfully to metallic materials: different types of steels, cast iron, etc., on diverse stress paths (reversed tension, rotating bending, cyclic torsion, etc.). It consists of detecting the onset of intrinsic dissipation or *damage indicator*, due to the thermomechanical coupling, as the specimen is excited by a fluctuating load. Intrinsic dissipation is thus a scalar parameter that is readily evaluated by infrared thermography. It provides a rapid evaluation of the fatigue strength of connecting rods, traditionally determined by very time-consuming procedures.

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