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INFRARE THERMOGRAPHY OF THERMOMECHANICAL COUPLINGS IN SOLIDS

M.P. LUONG¹⁻², D. PARGANIN² & J. LOIZEAU²

¹CNRS-MS Ecole Polytechnique 91128 Palaiseau France

²INSEP 11 Avenue du Tremblay 75012 Paris France

Email: luong@lms.polytechnique.fr

Abstract

The present paper aims to illustrate three advantages of infrared thermography as a non-destructive, real-time and non-contact technique to mechanically characterise solid materials. It permits observation of the macrostructural aspects of thermoplasticity describing damage and failure processes in diverse and various engineering materials and their components subjected to monotonous, cyclic or vibratory loading. It usefully suggests the definition of a *threshold of acceptable damage* TAD for materials related to sport equipment such as leather shoe, leather-like composites or sail synthetics. Particularly in case of metallic products or automotive components subjected to fatigue loading, this newly proposed method could evaluate in a non-destructive manner the *fatigue limit* FL in a very short time compared to traditional fatigue testing techniques that are much more time-consuming and excessively expensive. In addition owing to the thermomechanical coupling, infrared thermography readily describes the damage location, the dissipative regime and the evolution of structural failure.

1. Introduction

The thermal effect due to thermomechanical coupling at the tip of a moving crack has been investigated [4] within the framework of thermodynamics, taking into account stress and strain singularities. Internal energy dissipation was recognised by well-known scientists [1015-16-25-26-28]. Carrying out experiments on the cyclic twisting of cylindrical bars, Dillon [7] 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 . 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 in engineering materials under monotonous loading and metallic products subject to fatigue testing.

2. Heat production mechanism

Damage theories rely on assumed discontinuous phenomena at the microscopic scale [5]. Kachanov [13] 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 [6] 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. Since fatigue is generally caused by cyclic plastic strain, the plastic strain energy plays a very significant role in the damage process [9-12-22-23]. 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 [11], were poorly understood until recently because they occur unexpectedly at relatively low stress levels. Some progress has been made recently in design methods [2].

Despite this wealth of methods developed by engineers over the years, the principal question that remains unanswered is this: 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 either: 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 [3], or as a laboratory technique for investigating damage, fatigue, and failure mechanisms occurring in engineering materials [17-18]. 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.

3. Thermomechanical coupling in solids

The development of the thermo-elastic-plasticity equations [1-7-10-14] leads to the following coupled thermomechanical equation:

$$\rho C_v \dot{T} = r_0 + K \nabla^2 T - \left(\beta : \overset{(4)}{\underline{\underline{D}}} : \dot{E}^e \right) T + S : \dot{E}^I$$

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, $\overset{(4)}{\underline{\underline{D}}}$ 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. 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 a significant 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 a highly 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.

4. Infrared thermographic technique

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. A scanning camera, analogous to a television camera, uses 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 greater the emitted energy. Differences of radiated energy correspond to differences of temperature. The AGA 782 SW infrared scanner unit in use comprises the following:

- (a) a set of infrared lenses which focuses the electromagnetic energy radiating from the object being scanned, into the vertical prism;
- (b) an electro-optical mechanism which discriminates the field of view into 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;
- (c) 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;
- (d) 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 $5.6 \mu\text{m}$;
- (e) a liquid nitrogen Dewar that maintains the InSb detector at a very low temperature of $-196 \text{ }^\circ\text{C}$, allowing a very short response time of about one microsecond; and
- (f) 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, we can calculate the view-field temperature with a sensitivity of $0.1 \text{ }^\circ\text{C}$ at $20 \text{ }^\circ\text{C}$. This infrared device is used to scan specimens in the following two test programs.

5. Threshold of acceptable damage

On August 22, 1851, the yacht *America* raced a fleet of English cutters and schooners around the Isle of Wight. According to the legend, *America* easily prevailed. *America's* sails were unusual [8]. Through innovative technology, engineers have continually found ways to make stronger, lighter sails. The resistance of the fabric to stretching is especially crucial, as is its breaking strength. Also, yield strength, or the load beyond which the material is permanently elongated, is relevant, because even if they do not break, sails can be ruined by deformation. There is thus a need to detect damage using a very sensitive and non-invasive technique [27].

Before 1924 the whole sport footwear (upper and sole) was made in leather, thanks to its ability to absorb the sweating that is 6 to 8 times higher during a sport activity than as usual. Today leather is still well present in the sport footwears. Annually France produces 320 000 pairs for tennis, basket, training and footing, 200 000 pairs with staples and toes, 930 000 pairs for touring, 24 000 pairs for riding, and 180 000 pairs for dancing. Leather is a product made by stabilising through tanning the proteins of animal skins that are by-products of the meat industry. While about five-sixths of all the leather produced is used by the shoe industry, special uses of leather fill many real industrial needs. Through its many uses of boots, shoes, clothing, straps, harness or handbags, wallets, billfolds, leather novelties, etc., leather has become a most essential commodity of man. Softness, damage and strength behaviour is an important consideration in connection with designs or regulations. An other concern is to produce leather of uniform good quality, for example, which is acceptable to the shoe manufacturer and the wearer of the shoes. Balls for football games were made in leather. Since World Cup 1986 in Mexico, synthetic composites substituted leather. However they are mechanically considered as leather-like materials. A specimen of soccer ball envelope was tested under uniaxial tension test. *Figure 1* shows the load-displacement curve of this leather-like specimen. 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. Infrared thermography readily detects intrinsic dissipation announcing the occurrence of damage, preceding the failure of leather-like specimen. *Figure 2* presents the evolution of intrinsic dissipation when loading increases up to failure and thus defines a *threshold of acceptable dissipation or damage* (TAD), separating low and high regimes of dissipation or damage occurrence.

The process of tailoring leather-like products involves the transformation of a two-dimensional structure (planar sheet fabric) into a three-dimensional form. It necessitates the formation of extreme curvatures by sewing or fusing and pressing. The joining of different pieces of leather components is achieved by sewing with sewing threads. There are many problems associated with the performance of sewing threads during the sewing process that can reach very high speeds. During the stitching process, thread is subjected to complex kinematic and dynamic conditions. Tensile and bending stresses, that take place at very high speeds, localised heating that may cause reduction of strength of thermoplastic sewing threads by as much as 60 %. In addition the mechanics of the thread structure and their properties in the seams after sewing include seam strength. Stretch and pucker are also extremely important. Current design procedures for leather-like seams are based upon simplified assumptions of connection behaviour. The increased use of diverse types of seams by sewing and/or glueing suggests that a more thorough understanding of the behaviour of seams would be beneficial for upgrading design procedures. As infrared thermographic scanning offers new information on leather-like connection behaviour, refinement of design procedures can be made as needed and new, more effective, and specialised seam configurations can be contemplated. *Figure 3* presents a tension test on a soccer envelope seam. A threshold of acceptable dissipation or damage TAD for the seam appears on *Figure 4*. This experimental result shows that the process of leather-like seam could be optimised in order to meet a higher value for its TAD limit.

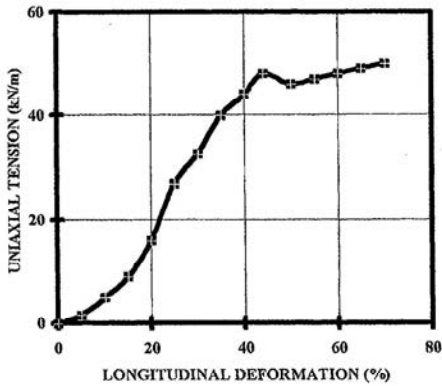


Figure 1. Tension-deformation of a specimen of football envelope.

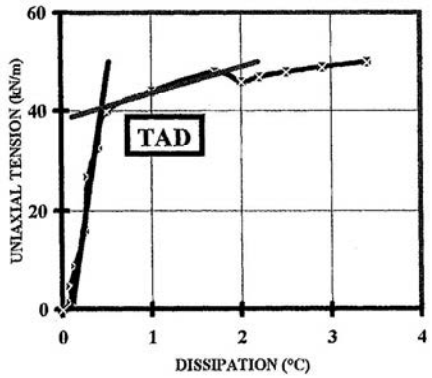


Figure 2. Corresponding tension-dissipation curve for the same specimen. The two straight lines define a threshold of acceptable damage (TAD). This means that the material fails if this load is exceeded.

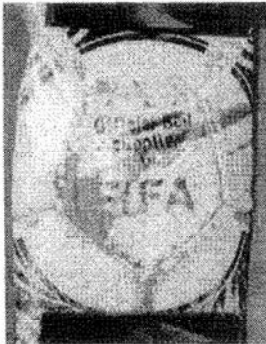


Figure 3. Tension testing on a soccer envelope seam.

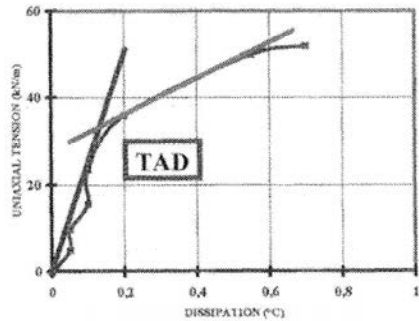


Figure 4. Tension-dissipation curve for a football envelope seam. The two straight lines define a threshold of acceptable damage (TAD). This means that the envelope seam fails if this load is exceeded.

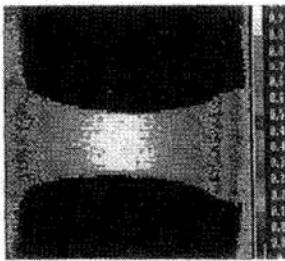


Figure 5. intrinsic dissipation of the specimen under 390 MPa after 6,000 load cycles (Temperature scale is given in °C).

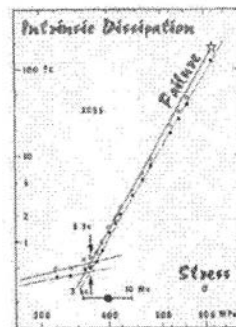


Figure 6. Graphical determination of fatigue limit (FL) of XC55 steel specimen.

6. Evaluation of fatigue strength

The material for the rotating bending tests was XC55 steel, quite extensively used 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 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 in the absence of failure, and lowered otherwise. Using standard methods of statistical analysis, we estimated the fatigue limit to be 399 MPa with a standard deviation of 41 MPa.

A series of five rotating bending tests has been scanned by the infrared system at different stress levels that were 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 uniformly high level. In addition, it allows examination of the surface which is undertaken at oblique angles, without degradation of sensitivity. The recommended paint coating also reduces surface reflections and ensures 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.

Computer-aided thermography software TIC 8000 allowed data reduction of thermal images that shows heat generation after 6,000 load cycles at 390 MPa (*Figure 5*). These thermal images provided 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 in the intrinsic dissipation regime of the loaded specimen. Experimental results are summarised in *Figure 6* which shows how fatigue limit is determined using a graphical procedure. The threshold of critical thermal dissipation is roughly the same for the 3,000 and 6,000 cycle curves. It corresponds to the value deduced from standard procedure. The star point at co-ordinates (600 MPa, 180 °C) represents the last load step at which failure occurred.

These experiments showed 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.

7. Concluding remarks

This work has demonstrated that material dissipativity is a highly sensitive and accurate manifestation of damage, owing to the thermomechanical coupling. Infrared thermography provides a non-destructive, real-time and no contact technique to observe the physical processes of degradation and to detect the occurrence of intrinsic dissipation. It readily evaluates the threshold of acceptable damage under monotonous loading and the fatigue limit in cases of fatigue testing.

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