



**HAL**  
open science

# Evaluation of the limit of acceptable damage for leather products using infrared thermography

Minh-Phong Luong

► **To cite this version:**

Minh-Phong Luong. Evaluation of the limit of acceptable damage for leather products using infrared thermography. *Nondestructive Evaluation Techniques for Aging Infrastructures & Manufacturing*, Mar 1999, Newport Beach, United States. pp.84-95, 10.1117/12.339836 . hal-00116560

**HAL Id: hal-00116560**

**<https://hal.science/hal-00116560v1>**

Submitted on 12 Mar 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Evaluation of the limit of acceptable damage for leather products using infrared thermography

Phong M. Luong\*<sup>a</sup>

<sup>a</sup>CNRS-LMS, Ecole Polytechnique, 91128 Palaiseau, France

## ABSTRACT

The paper aims to illustrate three advantages of infrared thermography as a nondestructive, noncontact and real time technique (a) to observe the progressive damage processes and mechanisms of leather failure, and (b) to detect the occurrence of intrinsic dissipation localization. The parameter, investigated in this paper, is the heat generation due to intrinsic dissipation caused by anelasticity and/or inelasticity of leather. It readily describes the damage location and the failure evolution of leather for sport foot-wear.

**Keywords:** dissipative behavior, infrared scanning of failure processes, intrinsic dissipation localization, leather damage, leather shoe, noncontact and nondestructive testing, seam strength, thermomechanical coupling.

## 1. INTRODUCTION

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 stabilizing 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 behavior are 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.

As with other materials in response to these problems, diverse damage analysis methodologies have been developed in recent years, which isolate the factors affecting crack initiation and growth, and enable the prediction of their cumulative effect on the mechanical performance of structural components. They are based on (i) the formulation of analytical models for damage crack and growth, and (ii) the acquisition of supporting baseline data and validation of such models by means of a comprehensive testing procedure.

The present paper proposes the use of infrared thermography as a nondestructive, noncontact and real time technique to examine the mechanisms of damage and to analyze the processes of failure of leather. The aim of this study is to illustrate the onset of damage process, stress concentration and heat dissipation localization in loaded zones. In addition, this technique can be used as a nondestructive method for inspection and evaluation of stress concentration in manufactured leather products.

## 2. MAIN CHARACTERISTICS OF LEATHER

Leather is a product of biological origin<sup>7</sup>. It is a very variable and heterogeneous material. The mechanical properties are mainly dependent on inhomogeneous composition and anisotropic structure of skins. The different fibers of the grain and corium layers are interwoven at the boundary line, making it difficult to define the precise location of this interface. Random interweaving collagen fibers or bundles containing fibers, form a complex fiber matrix and constitute the fibrous structure of the leather.

\* Correspondence: Email: luong@lms.polytechnique.fr; Tel: 33 1 6933 3368; Fax: 33 1 6933 3026.

Mechanically, collagen fibers are strong in the direction of the fiber axes<sup>24-36</sup>, and the elongation at failure is about 2 %. In the dead animal skin, the fibers are set in a matrix of natural binding agents such as blood, etc. These agents are removed during the tanning process to create an open structure of fibers that is held together by the interwoven arrangement of the fibers. During the later stages of the tanning process, the pores between the fibers are partially filled with oils and greases which determine the subsequent behavior of the leather. The partial filling of the zones between adjacent fibers produces a porous matrix structure. The degree with which the larger fibers are broken and separated into smaller fibrils has an influence on the strength and other physical properties of leather.

Under applied uniaxial loading this type of structure enables the fibers to rotate and to slide relatively to each other. The breaking load measured in any strength test is directly related to the number of fibers which become involved in the test prior to rupture. The tensile strength is higher in the direction parallel to the backbone than that in the direction at right angles to it; but the strains at failure have an inverse directional dependence<sup>45</sup>. On initial monotonic loading for a typical test, the stress increased proportionally with elongation. The mechanism of deformation is due to fiber rotation. Subsequently for large strains, the behavior is nonlinear with the stress, reaching a plateau at failure. Deformation takes place by the combined mechanism of fiber rotation and of slippage between adjacent fibers.

Very extensive work has been carried out by the Technical Committee of the Upholstery Leather Group in attempting to set specifications, and develop methods that can be related realistically to service performance<sup>2-14,28</sup>. Particular tests and specifications are useful for automotive industry: breaking strength, elongation (stretch), stitch tear resistance (static and dynamic), tongue tearing, bursting strength, abrasion resistance, flex resistance, etc.

Tensile strength was the first strength test applied to leather and at the present time, it is more generally applied than any other of the mechanical tests used<sup>30</sup>. Breakage in the tensile test may be considered to result from either the rupture of chains or the slipping of adjacent chains. The reason for the high tensile strength of the native fibers is believed to be their predominately primary valence chain structure. A large amount is required to break such chains.

Stitch tearing test was introduced recently for the evaluation of leather with regard to strength of seams. It was devised to simulate the behavior of the stitches in shoes under service conditions. It has become quite popular because only a small amount of leather is required to make the test and the test procedure is simple. The stitch tearing test depends on the load which may be supported by the leather before a tear is started, and for this reason it is a valuable test in the evaluation of seams.

Tongue tear test is a simple tear test. A piece of leather about 1 inch wide and 6 inches long is split at right angles to the grain and flesh sides for about two-thirds of its length. The end of one of the pieces formed by the split is put in one jaw of the testing machine and the other end is placed in the other jaw. Tongue tear differs from both the tensile strength test and the stitch tear test in that the strength in the direction perpendicular to the backbone is higher than that in the parallel direction.

Burst test gives an average value of the strength in both directions. A specimen of leather 4 by 4 inches is clamped between two corrugated steel plates having an aperture 1 3/8 inches in diameter. This adapter is placed in one jaw of a testing machine. In the other jaw a plunger, hemispherical at the tip, 2 inches long and 1 inch in diameter, is fastened. The force is applied to the plunger so that it moves at the rate of 1 inch per minute. The force required to crack the grain of leather and that required to burst the leather are recorded. The burst test is closely related to performance in shoe-making. Pulling the upper over the last applies forces similar to those applied in the test. Since the first failure noted is generally cracking of the grain, it may also be used for measuring the tenderness of the grain.

Nondestructive and noncontact tests are thus needed to define leather and leather product properties (1) to establish strength, (2) to optimize design values and (3) to insure quality control.

### **3. QUANTITATIVE MEASUREMENT OF DAMAGE**

The term damage is commonly used in various 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 fatigue crack extension. Continuum mechanics assumes that damage is induced by the initiation and growth of microcavities. Damage theories usually rely on assumed discontinuous phenomena at the microscopic scale<sup>10</sup>. Damage parameters, considered as internal variables, are introduced according to the following main approaches:

### 3.1. Effective stress

In order to develop the concept of an effective stress, Kachanov<sup>23</sup> 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. Because 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 that are developed for analyzing fatigue in metals, creep and creep-fatigue interaction<sup>29</sup>.

### 3.2. Plasticity formalism

The plasticity formalism describes the inelastic behavior 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<sup>18</sup>. Taking into account the most fundamental aspects of inelastic deformation and neglecting the details at the microstructural level, Mroz<sup>37</sup> suggests phenomenological constitutive models that are widely used in engineering applications.

### 3.3. Micromechanics

The micromechanical approach aims to provide a ready understanding of the damage mechanism at the macroscale. A random macrostructure is generated by computation from the known behavior of microstructures, each microstructure being characterized by a finite number of parameters<sup>46</sup>.

On the basis of micro- and macroscale relationships, Dang-van<sup>15</sup> 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 unfavorably 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<sup>41</sup> and Deperrois<sup>16</sup> for a better fitting with experimental results.

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

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

Infrared thermography has been successfully used as an experimental method for detection of plastic deformation during crack propagation of a steel plate under monotonic loading<sup>9</sup> or as a laboratory technique for investigating damage, fatigue and creep mechanisms occurring in engineering materials<sup>31-32-33-34</sup>.

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 microcracking is induced by loading, the plastic dissipation, generated in leather or in structural leather product, is readily detected in this study by infrared thermography owing to the thermomechanical coupling.

## 4. THEORETICAL 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 assumptions<sup>3-17-19-25-26</sup>.

1 • The basic thermomechanical quantity describing thermodynamic processes : the motion  $x$ , the second Piola-Kirchhoff stress tensor  $S$ , the body force per unit mass  $b$ , the Helmholtz free energy  $\psi$ , the specific entropy  $s$ , the heat supply  $r_0$ , the absolute temperature  $T$ , the heat flux vector per unit area  $q$ , the elastic strain tensor  $E^e$ , the inelastic strain tensor  $E^l$  and a set of internal state variables  $\alpha^{(l)}$  characterizing the material.

2 • 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.

i) Balance of linear momentum

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

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

ii) Balance of energy

$$\rho (\dot{\psi} + \dot{s}T + s\dot{T}) = \rho \dot{e} = S : \dot{E} - \text{div } q + r_0 \quad (2)$$

The balance laws are assumed not to change from those in thermoelasticity. This postulate leads to the use of internal state variable-type thermodynamics<sup>26</sup>.

iii) 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  $\rho$  ( $\text{kg.m}^{-3}$ ) is the mass unit in the reference configuration,  
 $e$  the specific internal energy and  
 $E$  the Green-Lagrange strain tensor  $E = \frac{1}{2}(\nabla x^T \cdot \nabla x - 1)$ .

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.

3 • The constitutive assumptions describing the material response and abiding the compatibility of the constitutive equations with the fundamental equations of mechanics.

When adopting the separability of the strain tensor

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

where  $\beta$  is the coefficient of the thermal expansion matrix and  $T_R$  the reference temperature, the requirement of the second law of thermodynamics yields:

i) The response functions  $S$ ,  $\psi$  and  $s$  are independent of the temperature gradient  $\nabla T$ .

ii)  $\psi$  determines both the stress tensor and the specific entropy through

$$S = \rho \frac{\partial \psi}{\partial E^e} \quad \text{and} \quad s = -\frac{\partial \psi}{\partial T} + \frac{\partial \psi}{\partial E^e} : \beta$$

iii)  $\psi$ ,  $\dot{E}^I$  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 :

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

Assuming

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

and the Fourier heat conduction law

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

The coupled thermomechanical equation is written as follows:

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

where  $\beta$  denotes the coefficient of the thermal expansion matrix,  
 $C_v$  (J.kg<sup>-1</sup>.K<sup>-1</sup>: Joule per kilogram per Kelvin degree) the specific heat at constant deformation,  
 $D$  the fourth-order elasticity tensor,  
 $e$  the specific internal energy,  
 $K$  (W.m<sup>-1</sup>.K<sup>-1</sup>: Watt per meter per Kelvin degree) the thermal conductivity and finally  
 $T$  the absolute temperature.

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

This coupled thermomechanical equation defines the potential applications and various uses of 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, and particularly in cases of difficult environments.

#### 4.1 - Heat sources

The first term is related to the existence of sources or sinks of heat in the scanning field<sup>13</sup>. The surface heat patterns, displayed on the scanned specimen, may be established either by external heating, referred to in 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<sup>43</sup>. In the following reported experiments, thermal noise, generated by test conditions (gripping of specimens, environmental temperature), may sometimes obscure the intrinsic dissipation of the tested specimen.

## 4.2 - Thermal conduction

The second term on the right hand side of the 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<sup>35</sup>.

Where an unsteady state exists, the thermal behavior 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  $\alpha = K/C$  ( $m^2 \cdot s^{-1}$ ) that 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 characterize a delamination in a composite by the break, caused in the temperature time history<sup>5</sup>.

## 4.3 - 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 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 loading. 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<sup>40</sup>.

## 4.4 - Intrinsic dissipation

The last term defines the energy dissipation, generated by viscosity and/or plasticity. Internal energy dissipation was recognized by many scientists<sup>38-39-42</sup>. The work done to 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 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. 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 nonlinear coupled thermomechanical analysis. The quantification of this intrinsic dissipation for engineering materials is an extremely difficult task without infrared thermography<sup>12-20-21-22</sup>.

The infrared thermographic technique is mainly concerned with differences in temperature (or thermal gradients) that exist in a material rather than the absolute value of temperature.

Ignoring the significance of the coupled thermomechanical equation, an attempt has been made without success by Leaity and Smith<sup>27</sup> to monitor thermoemissions during fatigue crack propagation tests. The used SPATE technique 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 nonlinear coupled thermomechanical effect within the framework of a consistent theoretical background.

## 5. INFRARED THERMOGRAPHY OF LEATHER

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<sup>4</sup> in order to demonstrate the local heating at the tip predicted by Barenblatt et al.<sup>6</sup>. Attempts have been made to measure and characterize the heat generated during the cyclic straining of composite materials<sup>43-44</sup>. The scanning infrared camera has been used to visualize the surface-temperature field on steel and fiberglass-epoxy composite samples during fatigue tests<sup>11</sup>.

### 5.1. Infrared scanner

For this work, a scanning camera is used which is analogous to a television camera<sup>1</sup>. It utilizes 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 color and monochrome video system. Response times are shorter than one microsecond. Temperature differences in the heat patterns are discernible instantly and represented by several distinct hues.

The quantity of energy  $W$  ( $W \cdot m^{-2} \cdot \mu m^{-1}$ ), 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 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 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 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  $3.5 \mu m$  to  $5.6 \mu m$ ,
- A liquid nitrogen Dewar which maintains the InSb detector at a temperature of  $-196^\circ C$  allowing a very short response time of about one microsecond, and
- A control electronics with preamplifier which produces a video signal on the display screen.

Since the received radiation has a nonlinear relationship to the object's temperature, and can be affected by atmosphere damping and includes reflected radiation from object's surroundings, calibration and correction procedures have to be applied. Knowing the temperature of the reference, the object's 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.

### 5.2. Experiments on a leather specimen under uniaxial tension

Chrome-tanned calfskin of thickness 0.98-1.02 mm was selected for the uniaxial tension test. Figure 1 shows the load-displacement curve of a leather specimen.

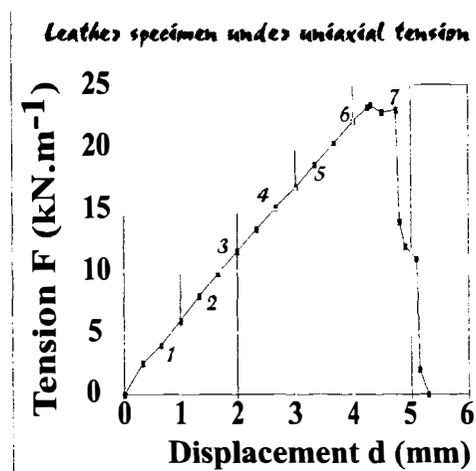


Figure 1. Force-displacement curve for tensile strength determination of leather.

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-color isotherm display, was used to record the bulk of the heat emission data. That device displays a ten-color calibrated surface-temperature picture of the specimen. Infrared thermography readily depicts intrinsic dissipation localization announcing mechanisms of damage preceding leather failure. Figure 2 shows a drastic change of dissipative regime before failure, evidencing the occurrence of damage in leather specimen.

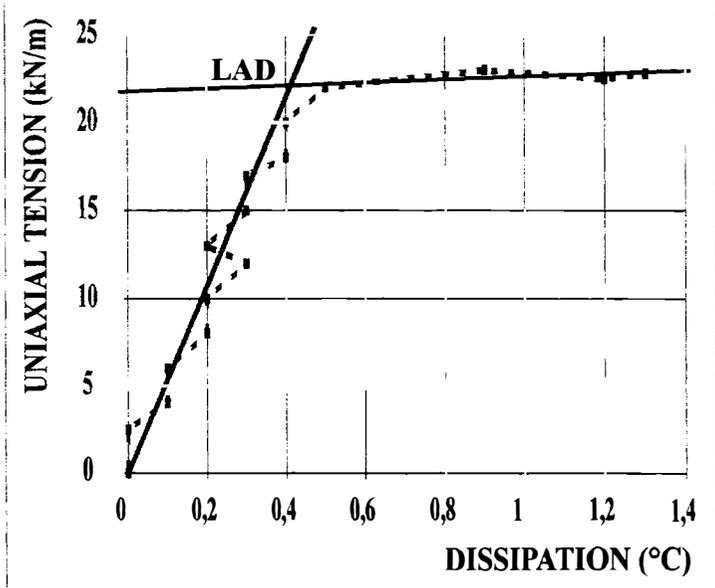


Figure 2. Definition of the limit of acceptable damage for leather subject to uniaxial tension (temperatures are given °C).

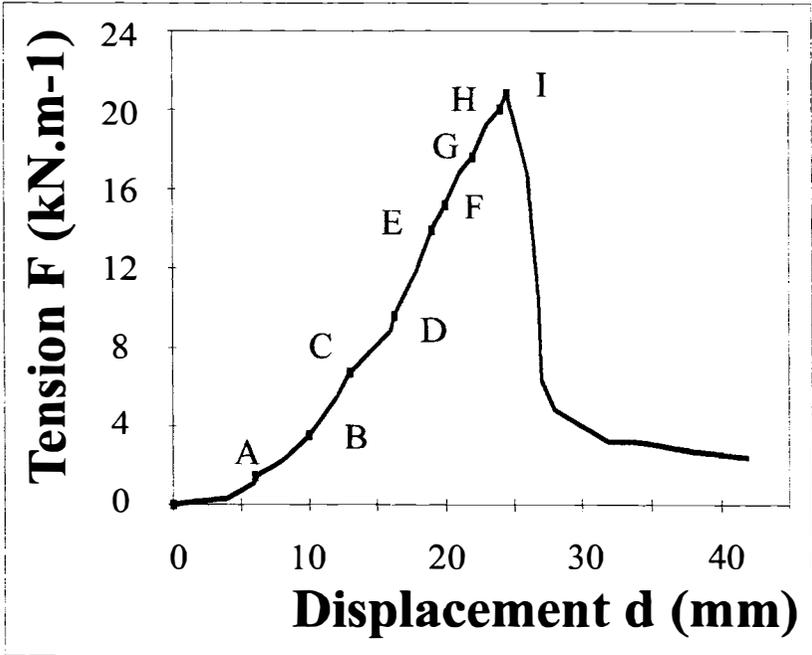


Figure 3. Load-displacement curve of a leather seam.

### 5.3. Infrared thermographic scanning on leather seam

The process of tailoring leather 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, localized 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 seams are based upon simplified assumptions of connection behavior. The increased use of diverse types of seams by sewing and/or glueing, suggests that a more thorough understanding of the behavior of leather seams would be beneficial for upgrading design procedures. As infrared thermographic scanning offers new information on leather connection behavior, refinement of design procedures can be made as needed and new, more effective, and specialized seam configurations can be contemplated.

Figure 3 presents a tension-displacement curve obtained on a common shoe leather seam. Typical intrinsic dissipation of this leather seam between 2 levels E and D of tensile loading is shown in Figure 4 and 5. A limit of acceptable dissipation or damage **LAD** for the seam appears on Figure 6. This experimental result shows that the process of leather seam could be optimized in order to meet a higher value for its LAD limit.

D - C

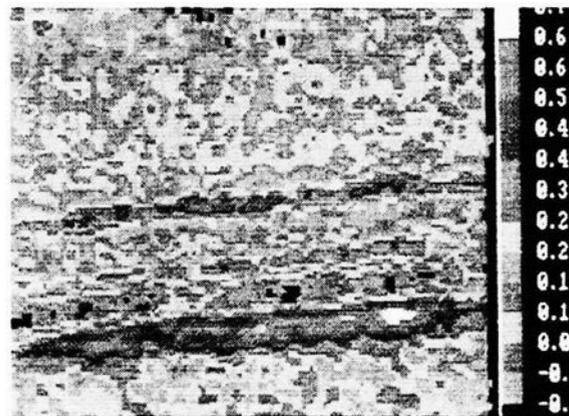


Figure 4. Intrinsic dissipation between tension levels D and C detected on the seam specimen ( $\Delta T$  are given  $^{\circ}C$ )

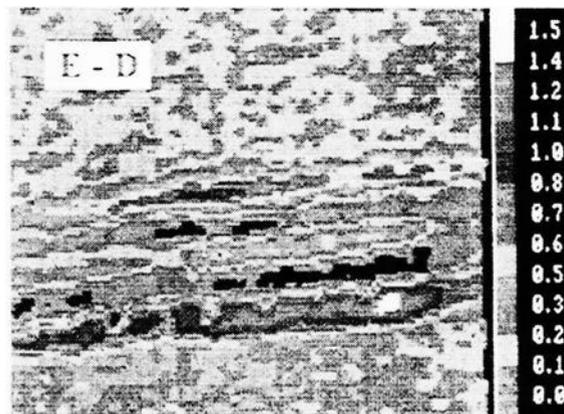


Figure 5. Intrinsic dissipation between tension levels E and D detected on the seam specimen ( $\Delta T$  are given  $^{\circ}C$ )

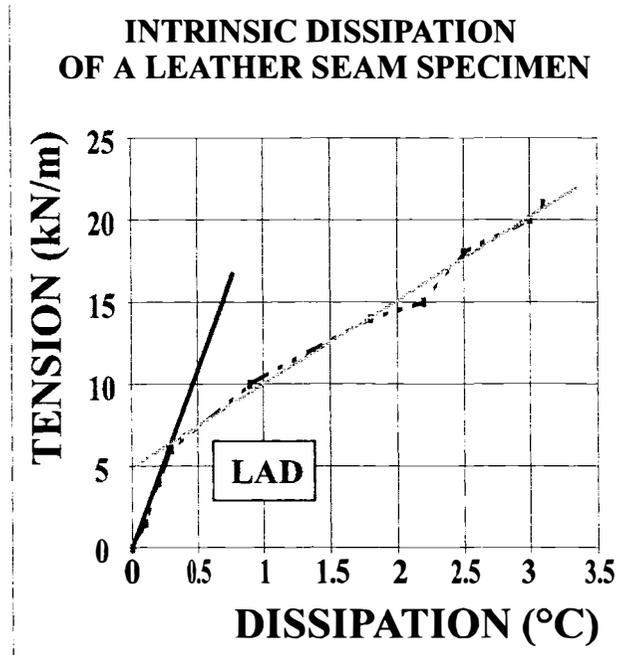


Figure 6. Definition of the limit of acceptable damage for leather seam subject to uniaxial tension (temperatures are given °C).

## 6. CONCLUDING REMARKS

This work has demonstrated that the *dissipativity* of the tested leather under tension is a highly sensitive and accurate *manifestation of damage*.

Owing to the thermomechanical coupling, infrared thermography provides a nondestructive, noncontact and real time test to observe the physical process of leather degradation and to detect the occurrence of intrinsic dissipation. Thus it readily gives a measure of the leather damage and permits to evaluate the limit of a progressive damaging process under load beyond which leather is susceptible to failure.

Infrared thermographic scanning of a typical leather seam, loaded in tension, provides interesting insights on load transfer in seam, improving our understanding of stress distribution within connections, far beyond the elastic domain and up to failure.

It is of particular interest that the method allows not only qualitative work such as finding flaws, defects or weakness zones, but also quantitative analysis of the effects of flaws and defects on strength and durability of leather 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 microcracking is generated by cyclic loading.

The main interest of this energy approach is to unify microscopic and macroscopic test data. The parameter *intrinsic dissipation* under consideration is a scalar quantity, easy to evaluate with accuracy. Subsequently it may suggest multiaxial design criteria, highly relevant for full scale testing on sport footwear or engineered products. It permits the definition of a *limit of acceptable damage* in leather or leather seam

Infrared thermography is an attractive and relatively unexplored technique for the nondestructive evaluation of failure in industrial materials and products. The main advantages of this technique are speed and noncontact operation. Signal processing techniques might be efficiently used to extract more quantitative information. Significant developments are expected soon, capitalizing on the recent progress in computing power and image-processing techniques. The opportunities offered by thermal techniques with remote operation and fast surface-scanning rates are particularly attractive for on-line applications.

## REFERENCES

1. AGA, Infrared System AB, "Thermovision 782", *Operating manual*, 1984.
2. K. T. W. Alexander, and R. G. Stosic, "A new nondestructive leather softness test", *J. Society of Leather Technologists and Chemists*, **77**, pp. 139-142, 1993.
3. D. H. Allen, "A prediction of heat generation in a thermoviscoplastic uniaxial bar", *Int. J. Solids Struct.*, **21** (4), pp. 325-342, 1985.
4. R. Attermo, and G. Östberg, "Measurements of the temperature rise of a fatigue crack", *Int. Fracture Mechanics*, **7**, pp. 122-124, 1971.
5. D. L. Balageas, A. A. Déom, and D. M. Boscher, "Characterization and nondestructive testing of carbon-epoxy composites by a pulsed photothermal method", *Materials Evaluation (American Society for Nondestructive Testing)*, **45**, pp. 461-465, April 1987.
6. G. I. Barenblatt, V. M. Entov, and R. L. Salganik, "On the influence of vibrational heating on the fracture propagation in polymeric materials", *IUTAM Symp. Thermoelasticity*, East Kilbride, 1968.
7. J. Bérard, et J. Gobillard, *Cuir et Peaux*, Presses Universitaires de France, 1951.
8. G. Bonnet, et P. Jouanna, "Vers une approche énergétique des mécanismes de ruine des massifs rocheux fissurés", *Rev. Industrie Minérale*, **7**, pp. 1-7, 1975.
9. H. D. Bui, A. Ehrlicher, et Q. S. Nguyễn, "Etude expérimentale de la dissipation dans la propagation de fissure par thermographie infrarouge", *C. R. Acad. Sci.*, **293**, Série II, Paris, pp. 1015-1018, 1981.
10. H. D. Bui, and C. Stolz, "Damage theories for brittle and ductile materials", *Fracture of Non-Metallic Materials*, ed. Herrmann and Larsson, pp. 33-46, 1987.
11. J. A. Charles, F. J. Appl, and J. E. Francis, "Using the scanning infrared camera in experimental fatigue studies", *Experimental mechanics*, **14**(4), pp. 133-138, April 1975.
12. A. Chrysochoos, and J. C. Dupré, "An infrared set-up for continuum thermodynamics", *Quantitative Infrared Thermography QIRT 92*, Eurotherm Series **27**, EETI, pp. 129-134, 1992.
13. P. Cielo, X. Maldague, A. A. Déom, and R. Lewak, "Thermographic nondestructive evaluation of industrial materials and structures", *Materials Evaluation (American Society for Nondestructive Testing)*, **45**, pp. 452-460, April 1987.
14. E. D. Compton, "Upholstery leather manufacturer", *The Chemistry and Technology of leather*, **III** (41), pp. 292-305, 1956.
15. K. Dang-van, *Sur la résistance à la fatigue des métaux*, Sciences et Techniques de l'Armement, Mémorial de l'Artillerie Française, **3**, 1973.
16. A. Deperrois, *Sur le calcul de limite d'endurance des aciers*, Thèse de Doctorat, Ecole Polytechnique, 1991.
17. O. W. Jr Dillon, "Coupled thermoplasticity", *J. Mech. Phys. Solids*, **11**, pp. 21-23, 1963.
18. J. W. Dougill, "Path dependence and a general theory for progressively fracturing solid", *Proc. Roy. Soc. Lond.*, **A**, **319**, pp. 341-451, 1983.
19. W. S. Farren, and G. I. Taylor, "The heat developed during plastic extension of metals", *Proc. Roy. Soc. Lond.*, **A** **107**: pp. 422-451, 1925.
20. A. Galtier, *Contribution à l'étude de l'endommagement des aciers sous sollicitations uni- ou multiaxiales*, Thèse de Doctorat ENSAM, Bordeaux, 1993.
21. A. H. I. Gomaa, *Corrélation entre la dissipation thermique d'une éprouvette en torsion alternée et sa limite d'endurance en fatigue*, Thèse de Docteur-Ingénieur en Mécanique Physique, Université de Bordeaux I, 1980.
22. T. Gross, *Calorimetric measurement of the plastic work of fatigue crack propagation in quenched and tempered 4140 steel*, Ph.D. thesis, Northwestern University, Evanston, August 1981.
23. L. M. Kachanov, "Time of rupture process under creep conditions", *Izv. Akad. Nauk. S.S.R. Otd. tekhn. Nauk.*, **8**, pp. 26-31, 1958.
24. J. R. Kanagy, "Significance of the results of some physical tests on upper leather", *J. Amer. Leather Chem. Assoc.*, **8**, pp. 112-148, 1954.
25. J. Kratochvil, and O. W. Dillon, "Thermodynamics of elasto-plastic materials as a theory with internal state variables", *J. Appl. Phys.*, **40**, pp. 3207-3218, 1969.
26. J. Kratochvil, and O. W. Dillon, "Thermodynamics of crystalline elastic-visco-plastic materials", *J. Appl. Phys.*, **11**, pp. 1470-1479, 1970.
27. G. P. Leaity, and R. A. Smith, "The use of SPATE to measure residual stresses and fatigue crack growth", *Fatigue Fract. Engng Mater. Struct.*, **12**(4), pp. 271-282, 1989.

28. P. Kronick, A. Page, and M. Komanowsky, "An acoustic emission study of staking and fatliquor", *J. American Leather Chemists Association*, **88**, pp. 178-186, 1993.
29. J. Lemaitre, et J. L. Chaboche, "Aspect phénoménologique de la rupture par endommagement", *J. Mécanique Appliquée*, **2**(3), 1978.
30. J. Lin, and D. R. Hayhurst, "Constitutive equations for multi-axial straining of leather under uni-axial stress", *Euro J. Mech., A/Solids*, **12**(4), pp. 471-492, 1993.
31. M. P. Luong, "Characteristic threshold and infrared thermography of sand", *Geotechnical Testing GTJOD5*, vol. **9**, N° 2, pp. 80-86, 1986.
32. M. P. Luong, "Infrared thermovision of damage processes in concrete and rock", *Engineering Fracture Mechanics*, vol. **35**, N° 1-2-3, pp. 127-135, 1990.
33. M. P. Luong, "Infrared thermographic characterization of engineering materials", *SPIE's 1990, Int. Symp. Optical & Optoelectronic Applied Science & Engng*, Series 1314, Infrared Technology XVI, pp. 327-338, San Diego, July 1990.
34. M. P. Luong, "Infrared thermography of fatigue in metals", *Int. Conf. Thermal Sensing and Imaging Diagnostics Applications*, SPIE 1682 Thermosense XIV, pp. 222-233, Orlando, April 1992.
35. P. V. Jr McLaughlin, M. G. Mirchandani, and P. V. Ciekurs, "Infrared thermographic flaw detection in composite laminates", *J. Engng Materials & Technology*, ASME, **109**, pp. 146-150, April 1987.
36. R. G. Mitton, "Mechanical properties of leather fibres", *J. Soc. Leather Trades Chem.*, **29**, pp. 169-194, 1945.
37. Z. Mroz, "Phenomenological constitutive models for metals", *Modelling small deformations of polycrystals*, Elsevier, pp. 293-344, 1986.
38. Z. Mroz, and B. Raniecki, "On the uniqueness problem in coupled thermoplasticity", *Int. J. Engng Sci.*, **14**, pp. 211-221, 1976.
39. H. A. Nied, and S. C. Batterman, "On the thermal feedback reduction of latent energy in the heat conduction equation", *Material Sci. Engng*, **9**, pp. 243-245, 1972.
40. D. E. Oliver, "Stress pattern analysis by thermal emission (SPATE)", *Dynamic stress analyser*, Ometron Limited, U.K., **14**, pp. 1-28, Sept. 1986.
41. Y. V. Papadopoulos, *Fatigue polycyclique des métaux: une nouvelle approche*, Thèse de Doctorat, Ecole Polytechnique, 1987.
42. B. Raniecki, and A. Sawczuk, "Thermal effects in plasticity", *Z. Angew. Math. Mech.*, **55**, part 1, pp. 333-341, and part 2, pp. 363-373, 1975.
43. K. L. Reifsnider and R. S. Williams, "Determination of fatigue-related heat emission in composite materials", *Experimental Mechanics*, **14**(12), pp. 479-485, Dec. 1974.
44. K. L. Reifsnider, E. G. Henneke, and W. W. Stinchcomb, "The mechanics of vibrothermography", *Mechanics of Nondestructive Testing* ed. W. W. Stinchcomb, pp. 249-276, 1980.
45. W. T. Roddy, *Chemistry and technology of leather*, American Chemical Society Monograph 134, Reinhold Publishing Corp., 1956.
46. Y. V. Zaitsev, "Inelastic properties of solids with random cracks", *Mechanics of geomaterials*, J. Wiley, 1985.