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INFRARED STROBOSCOPY—A METHOD FOR THE STUDY OF THERMOMECHANICAL BEHAVIOUR OF MATERIALS AND STRUCTURES AT HIGH RATES OF STRAIN

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Abstract—An experimental infrared stroboscopy method is proposed for studying the thermomechanical behaviour of materials and structures under cyclic loading. A double stroboscope was devised and constructed on the basis of the following principle: the video signal delivered by a telethermographic camera is interrupted by an analog gate controlled by a flip-flop synchronized with the periodical excitation signal. Infrared stroboscopy enables us to measure adiabatic temperature variations during deformations which it has not so far been possible to study at high frequency for lack of adequate experimental means. An approach is hereby made in the study of elastic, viscoelastic and plastic deformation and of cracking. This method thus opens the way to fundamental experimental research on temperature-deformation relationships at high rates of loading. However complex the structrures to which it is applied, it is possible in particular with this method to locate the areas of maximum stress, to detect incipient plastic deformations and cracks and to follow their development.

1. INTRODUCTION

In recent years, infrared radiometry has made considerable progress from the technological point of view. Nowadays there are thermovision cameras capable of detecting a temperature variation of 1/10° Celsius around the ambient temperature. Although numerous applications of this technique have been developed in the industrial, military and medical fields, only a few deal with the mechanics of structures and vibrations.

The present study was carried out within the framework of a wider research project initiated by B. Nayroles on the applications of infrared radiometry to the study of mechanical structures[1–4].

A mechanical action applied to a point on a structure generates a certain quantity of heat, which leads to a temperature variation. In the case of a vibrating structure, both the temperature and the deformation are periodic. In the field of elasticity, for instance, with reversible deformations the temperature varies around an average, and therefore an infrared radiometry processing with an exposure much longer than the vibration period provides no information. If it is desirable, moreover, for the phenomenon to be considered as adiabatic, the frequency must be high. In order to highlight the temperature variations, it is consequently necessary to carry out the stroboscopic recording on the maximum and then on the minimum strain, for example.

The experimental infrared stroboscopy technique proposed for structures subjected to cyclic loading makes it possible to quantify adiabatic temperature variations during the occurrence of deformations, i.e. to carry out investigations which were hitherto impossible at high frequency for lack of appropriate experimental means.

2. PRELIMINARY EXPERIMENT

Before making a stroboscope it is necessary to make sure, both qualitatively and quantitatively, that the temperature variations involved are actually observable with the available AGA 680 videothermography camera, which has a limit of sensitivity ranging about 0.1°C.

Calculation of temperature variation

For a one-dimensional elastic medium, in the case of reversible adiabatic deformation, according to an equation proposed in 1881 by W. Thomson (Lork Kelvin)[5] the temperature variation is given by:

$$\Delta T_s = -\frac{\alpha T}{\rho c_\sigma} \Delta \sigma_s \tag{1}$$

related to the isentropic stress variation $\Delta\sigma_s$, with: α as the linear thermal expansion coefficient, T the absolute temperature, ρ the mass per unit volume and c_σ the specific heat at constant stress.

Tensile stress experiment.

A constant deformation-rate tensile stress experiment was chosen and it was proposed to compare the temperature variation obtained by means of infrared radiometry with (1).

It appears in (1) that a tension produces a calculable cooling of the test secimen in the elastic range. It is also known, however,[5, 6] that a plastic deformation, be it in tension or compression, always produces heat, which led us as a subsidary investigation to continue the tensile stress experiment up to failure. Expectations of the phenomenon are as follows. Up to the elastic limit, observation and measurements of the cooling phenonenon should be in keeping with the calculation and beyond the yield point a substantial rise in temperature should appear as indicated by the diagram in Fig. 1.

This is what was actually observed on specimens of various metals and alloys. For most of them, the experiment enables us to detect the yield point. The experiment was applied to more complex structures; here the elastic and plastic deformation areas show up immediately and it is even possible to quantify these results in the case of structures with small thicknesses[4, 7].

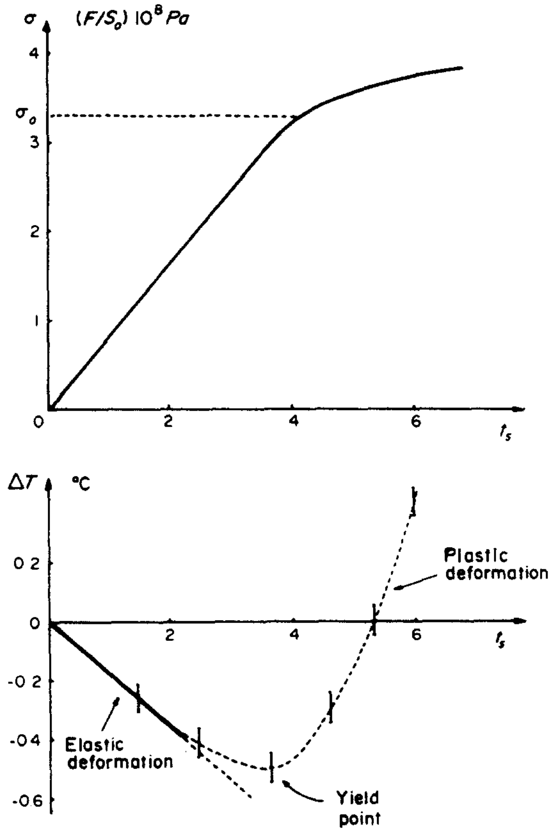

Fig. 1. Duralumin AU4G1 sample during tensile experiment with constant strain rate $\dot{\epsilon} = 1.13 \times 10^{-3}$/sec. In the lower graph, the calculated cooling is shown by a full line. The small vertical segments on the same graph represent the temperature obtained by infrared radiometry (each interval corresponds to a colour observed on the screen of the thermovision colour monitor as in Fig. 6).

3. STROBOSCOPY EQUIPMENT

Principle.

The principle underlying this device consists of interrupting the video signal by means of an analog gate controlled by a flip-flop synchronized with the periodical excitation signal.

Figure 2 shows the operation of the video signal gates, which are adjustable both in duration and in phase with respect to the excitation signal. For any selected value of the deformation or of the load applied to the structure under study, the elements of the picture appearing on the display unit are stored on a photographic film. After a certain number of cycles, the complete picture is reconstructed. As a consequence of the combination of the frame frequency and the gate opening frequency, the picture elements run vertically over the screen. In order to build up the complete picture within a short time, the loading frequency of the structure must be as remote as possible from any of the multiples of the frame frequency (16 per second)[3]. Figure 6, Plate I, shows an example of thermograms obtained.

Measurements

The problem of quantifying these results arises. Among the possible representations of the temperature chart of the object with the AGA-Thermovision system, the thermoprofile is the most suitable. With this device, an ordinate is selected among the 70 useful lines on the image of the sample, and the thermal amplitude versus the abscissa appears on a C.R.O. screen. The signal amplitudes along that line depend directly upon the energy level emitted by the object. After calibration by means of the black body, it is possible to draw a fine distinction between the temperatures. Infrared stroboscopy is adapted so as to display on a remanent oscilloscope screen a thermal profile for any given value of the deformation or of the stress applied upon the structure.

Subsequently, the stroboscope was perfected so as to generate two separate gates per cycle and build up the thermal profiles corresponding to the values of the deformation of the object under observation: maximum and minimum deformations, for instance see Figs, 2, 3 and 8.

In cases where it is sufficient to obtain thermal profiles along a single line, it is possible to operate on a "continued profile" basis. For this purpose, the vertical scanning prism of the camera has to be immobilized; operation is then restricted to horizontal scanning. It is then possible to obtain a thermal profile every 1/1600 second. The advantage of this modification is that it equips infrared stroboscopy to deal with structures subjected to loads of several thousands of cycles per second.

4. RESULTS

Metals

Various metal and alloy samples have been subjected to the stroboscopic experiment. Figure 3 shows an example of the photographic recordings obtained.

With a set frequency, varying the stress gives the diagram shown in Fig. 4.

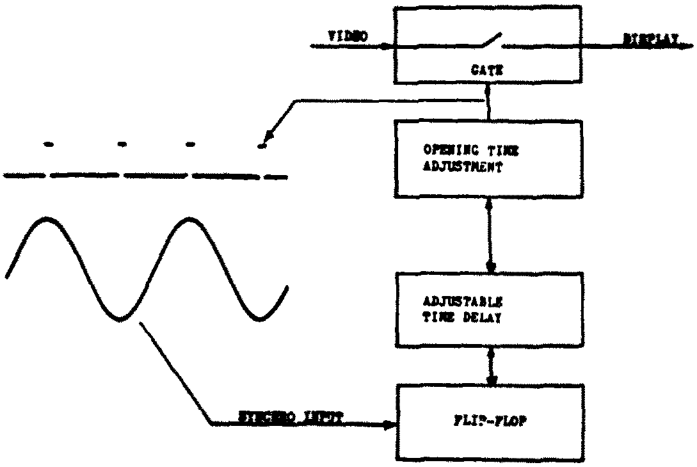

Fig. 2. Block diagram of the infrared stroboscope.

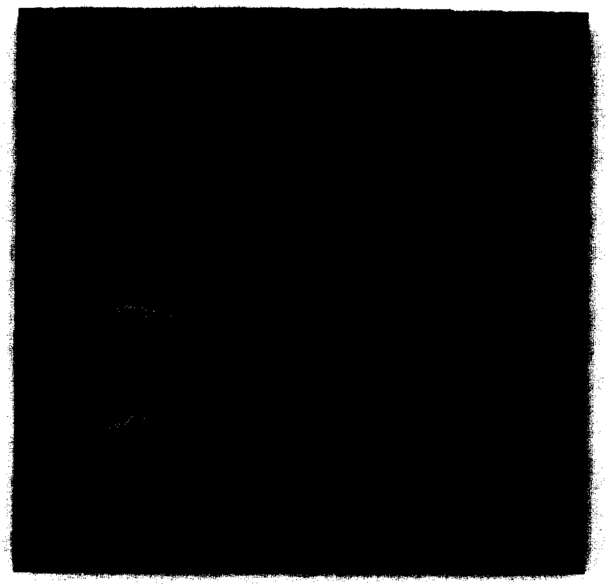

Fig. 3. Thermal profiles obtained by stroboscopic processing of a titanium plate. Upper trace, zero stress; lower trace, maximum stress equal to 50% of elastic limit. Frequency: 80 cps. The vertical shift leading to the coincidence of both traces gives the temperature variation.

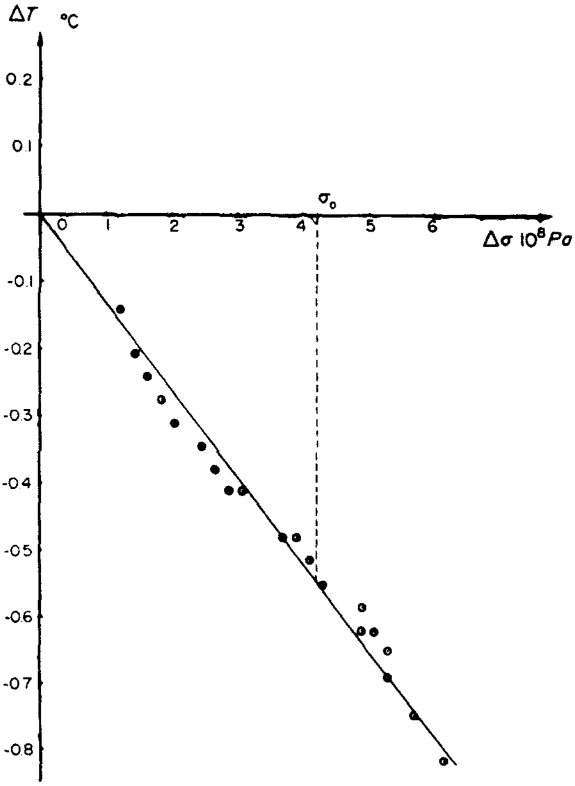

Fig. 4. Temperature variation versus stress variation of *T*40 titanium specimen under sinusoidal loading at 21 cps.

The following phenomenon, although not observed with titanium, was noted with an aluminium alloy. For stresses above the elastic limit (measured, equal to 3,3 10^8 Pa), the absolute value of the curve slope $\Delta T(\Delta\sigma)$ increases abruptly (see Fig. 5). Yet the experimental points have been obtained by scanning the stress difference with both an increasing and a decreasing excursion. It should not be forgotten that this diagram represents the temperature difference and not the temperature itself, which on an average increases considerably for stresses beyond the elastic limit as indicated by the process shown in Fig. 1.

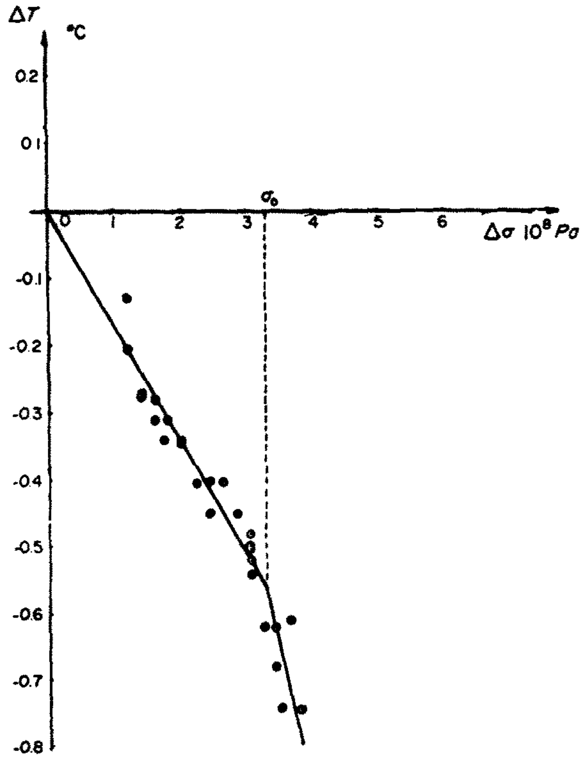

Fig. 5. Infrared stroboscopy AU4G1 specimen. Same conditions as in Fig. 4.

Elastoplasticity and cracking

We have applied the stroboscopic processing method to observing the propagation of a crack in a thin 60 mm wide titanium sheet subjected to the cyclic tensile experiment. The thermal pictures obtained (Figs. 6a and b) are built up from the magnetic recording of the experiment. Each colour on these pictures is representative of a temperature increasing from left to right on the scale at the lower section. (Colours at scale ends correspond to saturation inceptions.)

On Fig. 6(a), obtained under a zero stress, a small yellow spot can be observed. It corresponds to the maximum temperature at the head of the crack and it is surrounded by concentric circles representative of a temperature decreasing with the distance from the centre. Fig. 6(b), obtained under a maximum stress, shows the lips of the crack opening. A tension-induced cooling can be observed. In the present case it crorresponds to one of the ten levels of the colour scale: here one has 0.41°C.

Visco-elastic media

We also subjected high polymer specimens to the stroboscopic experiment. There appears a mean heating of the medium varying as the number of cycles and the rate of deformation, and which is caused by the international dissipation through viscosity, see Fig. 7.

This experiment requires the use of a dual stroboscope allowing temperature recording on both halfwaves of a same cycle. Figure 8 gives an example of a recording made under such conditions.

A development of the stroboscope method was evolved so as to represent heat development in a medium to which a simple sinusoidal tension has been applied. A thermoprofile is taken of the sample for which it is wished to measure temperature variation with respect to time. The principle consists of storing the stroboscope processed video signal on a remanent oscilloscope screen with a slow scanning rate compared with that of the camera, during one horizontal scan of the oscilloscope. For this purpose, the vertical scanning prism is put out of action in order to rid the video signal of the parasite signals that occur during clamping, and the traces

Fig. 7. PVC under sinusoidal loading corresponding to a deformation comprised between limits ranging about 0 and 10^{-2}. Frequency: 60 cps. Stroboscopy on zero stress: lower traces after 2s; middle traces after 6s; upper traces after 9.8s.

Fig. 8. Experiment similar to that of Fig. 3 on a PVC sample. In order to reduce and then evaluate the background noise restricting the sensitiveness of the method, the signal is filtered and several profiles, 5 in this case, are recorded both under zero stress and under maximum stress.

corresponding to the grey scale are eliminated by modifying the electronic circuit of the display unit.

It is to be noted that the sensitivity and accuracy of the stroboscopic method as a whole can be considerably improved by digitizing and subsequently processing the thermograms, whether in real time or from a recording[4].

5. CONCLUSION

An infrared stroboscopy method is proposed for studying the thermomechanical behaviour of materials and structures at high rates of strain. A double stroboscope was devised and constructed whereby fast temperature variations about a mean value can be measured at frequencies up to several thousand cycles per second.

Infrared stroboscopy makes it possible to bring to the fore and quantify the isentropic temperature variations that occur during elastic deformations. Beyond the yield point, unexpected behaviour of samples of aluminium alloy was observed. Infrared stoboscopy provides further valuable data for investigating crack propagation. Some initial results have been obtained in viscoelasticity and the average dissipation of mechanical energy into heat was

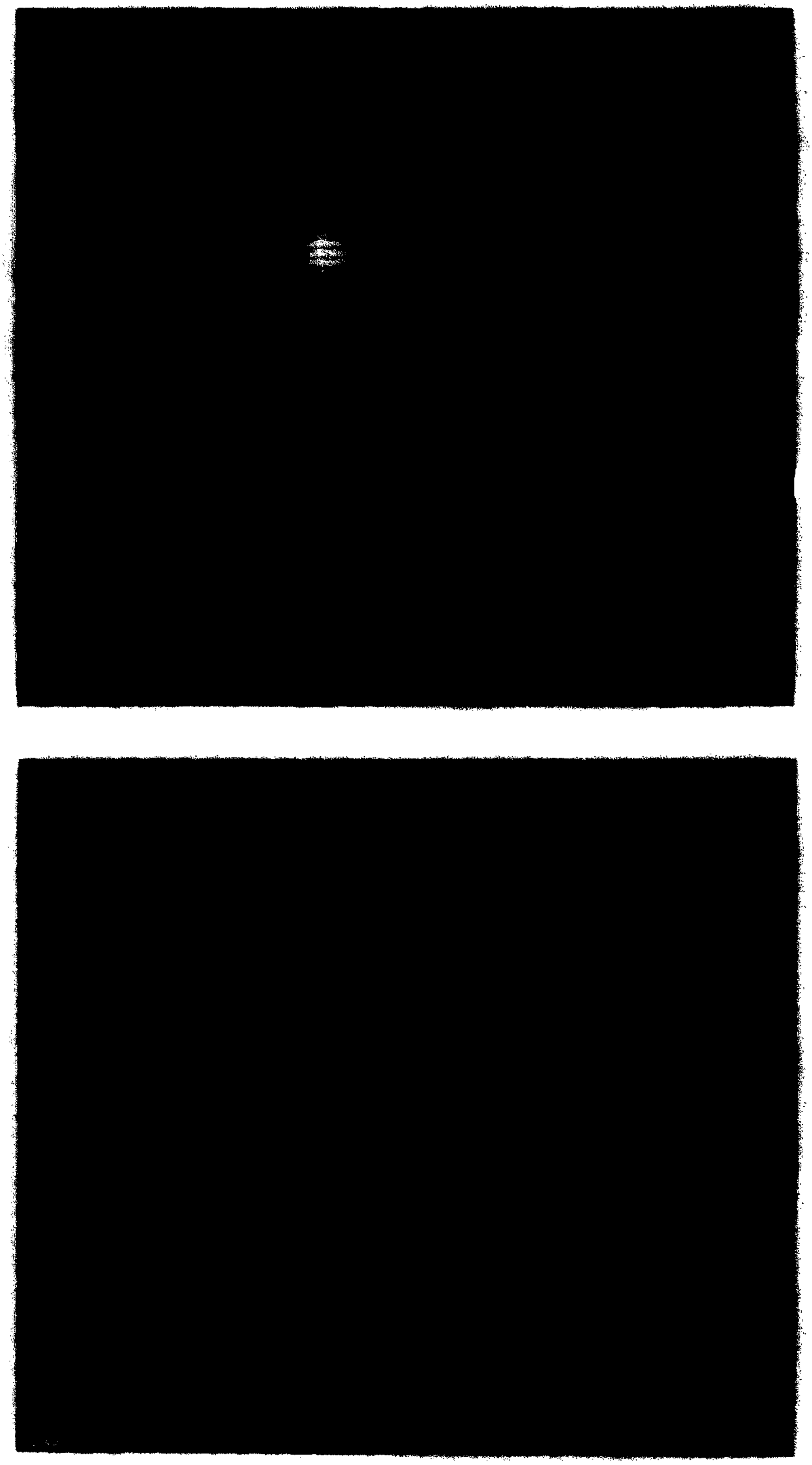

Fig. 6. Infrared stroboscopy of a crack propagating in a titanium plate. a: zero stress, b: maximum tension.

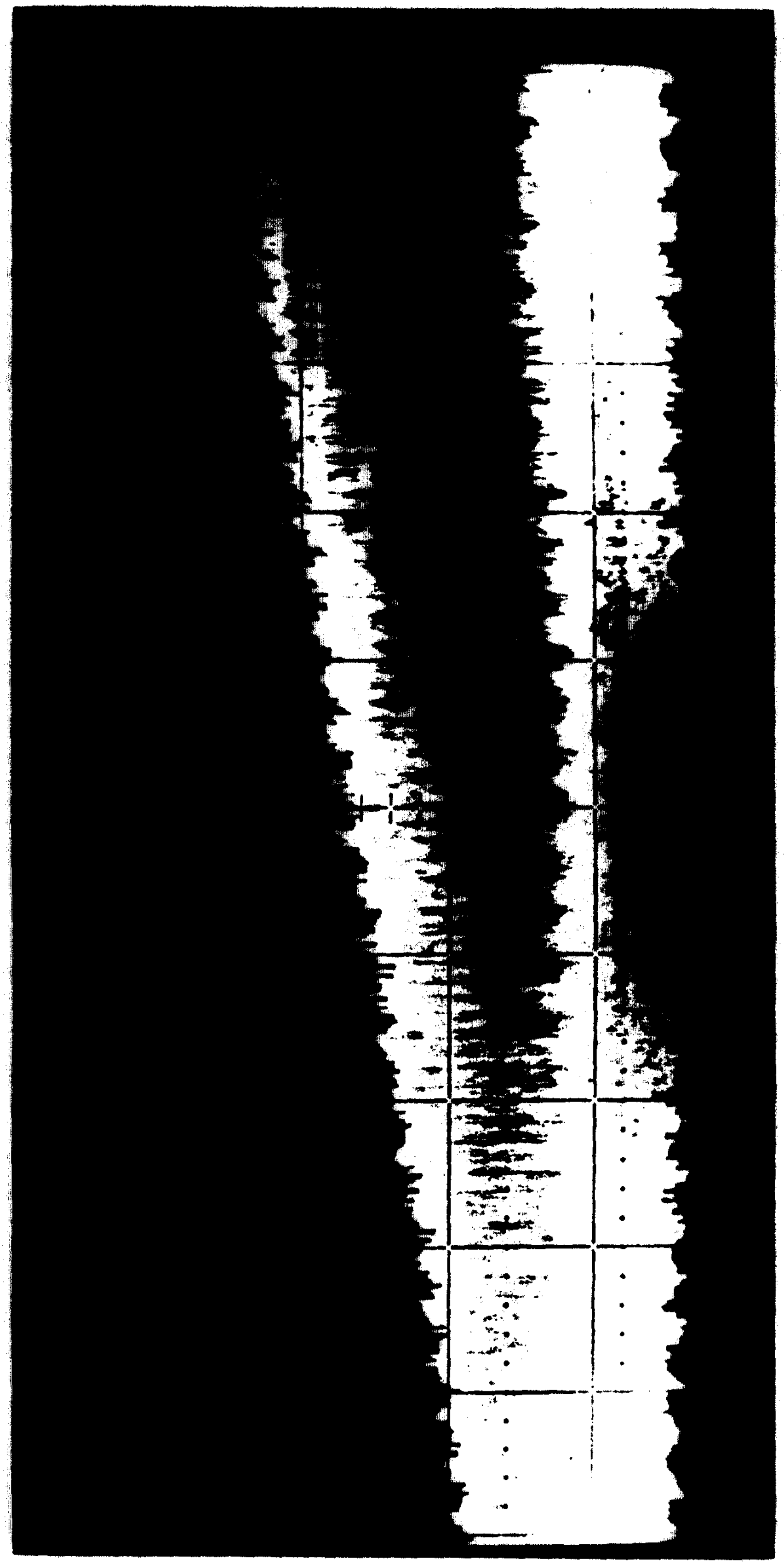

Figure. 9. Elastomer etc.,

evidenced. When applied to structures, this method makes it possible in particular to locate areas of maximum stress, to detect the onset of plastic deformations and cracks and to follow their development.

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