FRA/ORD-88/11
Internal Report

NBSIR 87-3653

Report No. ~~16~~ 15
Infrared Measurements of Heating and Cooling Emissions at a Crack Tip During Tensile and Cyclic Loading

Y. Huang, G. E. Hicho, and R. J. Fields

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Materials Science
Gaithersburg, MD 20899

Claire Orth

Office of Rail Safety Research
Federal Railroad Administration
Department of Transportation
Washington, DC 20590

February 1988

Prepared for
Federal Railroad Administration
Department of Transportation
Washington, DC 20590

NBSIR 87-3653

REPORT NO. 16
INFRARED MEASUREMENTS OF HEATING AND COOLING EMISSIONS AT A CRACK TIP DURING TENSILE AND CYCLIC LOADING

Y. Huang, G. E. Hicho, and R. J. Fields

U.S. DEPARTMENT OF COMMERCE
National Bureauof Standards
Center for Materials Science
Gaithersburg, MD 20899

Claire Orth

Office of Rail Safety Research
Federal Railroad Administration
Department of Transportation
Washington, DC 20590

February 1988

Prepared for
Federal Railroad Administration
Department of Transportation
Washington, DC 20590

U.S. DEPARTMENT OF COMMERCE, W. William Verity, ***Secretary***
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Director***

INFRARED MEASUREMENTS OF COOLING AND HEATING EMISSIONS AT A CRACK TIP DURING TENSILE AND CYCLIC LOADING.

Y. Huang[1], G.E. Hicho[2], and R.J. Fields[2]

ABSTRACT

A new thermographic method based on the measurement of infrared (IR) emission from the surface of a loaded body was used to study the cooling and heating in aluminum and steel specimens under tensile and cyclic loading. A typical test procedure using infrared to measure thermographic changes near the crack tip and the immediate surrounding area are described. Results are given for thermoelastic cooling phenomenon of metals during tensile process and IR cooling and IR heating emission at the crack tip during cyclic loading. Attention is drawn to the multiple phenomenon of IR cooling emission in the received signal as the applied load range increases beyond the elastic limit of the metals. A new application of the IR technique to the determination of the position of crack tip during cyclic loading is also presented.

1) Y. Huang, Guest worker from the Institute of Metal Research, Academia Sinica, China

2) G.E. Hicho and R. J. Fields, National Bureau of Standards, Institute for Materials Science and Engineering, Metallurgy Division, Gaithersburg, MD 20899

KEY WORDS

Aluminum, crack tip, infrared cooling emission, infrared heating emission, infrared crack extension recording, steel, stress concentration, and thermoelastic effects.

INTRODUCTION

In the practical uses of metals, the mechanical properties of metals and how they relate to engineering designs are of utmost importance. In using these designs, the thermal variations that occur inside the metals during the deformation process are often neglected. Currently, the thermal effect on metals during deformation is being used to explain the mechanical properties of metals.

As early as 1830, Kelvin discussed the thermoelastic effect (1), and a formalized description of this phenomenon was presented by Biot (2) in 1956. For the purposes of this paper, it is sufficient to state that, under adiabatic conditions, the following equation is used:

$$\Delta T_e = -CT\Delta\sigma \qquad (1)$$

where ΔT_e is the thermoelastic change in temperature T, C a constant, and σ the principal elastic stress. According to this expression, elastic tensile loading (a positive stress change) causes cooling, and elastic compressive loading causes heating. In a situation where a metal undergoes plastic deformation,i.e. beyond the yield, the temperature increment is defined as:

$$\Delta T_p = \gamma_B \sigma_p e_p \qquad (2)$$

where σ_p is the flow stress, e_p the plastic strain, and γ the coefficient of the conversion from plastic work to heat. For most metals, γ equals 0.98 (3). The cooling that occurred during elastic deformation was found to be very small, and in the past very few experimentalists measured this temperature change. Recently, the temperature change in a metal that occurred during an isentropic and adiabatic elastic deformation was found to be due to the thermoelastic effect. This effect was measured using a thermistor sensor and a thermographic technique (4,5), and was found for a series of metallic specimens, SAFC-40R steel (6), 6061-T6 aluminum (7), and stainless steel (8).

Recent work has covered the application of this new technique in the study of the thermoelastic IR cooling emission of metals. This paper presents the following new results: 1) the dynamic process of thermoelastic IR cooling emission; 2) the temperature distribution at a crack tip during elastic deformation; 3) the IR cooling and IR heating emission at a crack tip during fatiguing; 4) the multiple effect of IR cooling emission in metals under multi-cycle loading and unloading during elastic deformation; and 5) the ability to determine the relative crack length on the basis of the thermograms developed during the fatiguing process.

EXPERIMENTAL METHOD

Surface Infrared Emission Measurement

The basic IR thermographic technique was used for the surface IR emission measurement. This consisted of an infrared scanner which relayed signals to a combined monitor and control unit. The display presented on the monitor was photographed and stored on the tape so that a permanent record of results could be retained.

A typical thermogram is shown in Figure 1. The numbers 2, 5, 10, 20, 50, 100 on the top of the display correspond with the temperature ranges available on the instrument. The rectangular bright spot located at the top left in the figure indicates the temperature used, and in this instance, 2°C. The gray scale extending from the top to the bottom, and located on the right side of the display, shows the temperature for a particular brightness. In this case, 0 corresponds to a temperature T, and this was set by a separate noncalibrated control to suit the measurement being made. The units +0.5 and -0.5 correspond to the temperatures of T +1°C, and T -1°C, respectively. The bright spots in the figure all lie within -0.45°C of each other. The temperature, in relation to the arbitrary reference temperature T, is given by the position of the bring horizontal line on the scale lines. As shown in Figure 1 the bring spots, which are effectively an isotherm, represent a temperature of T+(-0.23 x 2 (temperature range)) ± 0.05°C. Thus this isotherm could be used to measure the temperature at any point on the body being viewed relative to the reference temperature, T. This was subsequently achieved by adjusting the isotherm level until the area of interest was illuminated by bright spots.

In the infrared emission measurement technique, the calibration curve is as follows:

$$I = \frac{A}{(C \cdot e^{B/T} - 1)} \tag{3}$$

where I is the thermal value in isothermal units corrected to T, T the object temperature in degrees Kelvin, and A, B, C are calibration constants. The constants, which correspond to the different infrared wavelength ranges used, are shown in Table 1.

Table 1. The parameters used in the IR thermal calibration curves.(9)

IR wavelength range	A	B	C
SW 3 - 5.6 μm	351344	2787	1.17
LW 8 - 14 μm	39234	1394	6.79

By determining the temperature at two points using the above equation, the temperature difference between them can be obtained. Using equation 3 in the system used, two of these isotherms could be displayed at once.

In equation 3, it is not possible to determine the absolute temperature on the surface, unless a temperature reference is introduced into the thermographic procedure. However, from the point of view of material being evaluated, i.e. in fatigue or crack growth, it is the temperature differences (i.e. IR emission) within the specimen that are more important, rather than absolute temperature. Hence, the system is well suited to the application.

The IR emission measurement made with the IR system assumes that the object being studied is a perfect black body, meaning that it has an emissivity of 1. In practice, the specimens considered were found to have a lower emissivity, 0.2 - 0.4. In order to increase the emissivity of the specimen to about 0.9, an infrared transparent coating was applied. The errors arising from using this coating were expected to be minor for the temperature differences considered, and were generally less than the errors encountered in the measurement system. These errors have therefore been neglected in this work.

Test Procedure

The emission tests were carried out in a servocontrolled hydraulic test machine on specimens prepared from aluminum, low carbon steel, and stainless steel. The dimensions of the compact tension specimens were 32 mm (width), 30.5 mm (height), and 12.8 mm thick. The specimens that contained a center hole with double saw cuts were 180 mm wide by 40 mm high, and 3 mm thick.

In the elastic deformation range, the tensile loading rate is 0.5 mm/min. During fatigue, the load cycle was approximately sinusoidal, and the cyclic frequency was 10 Hz. Cyclic load limits for each specimen were selected so as to give a satisfactory signal level overall.

The distance between the specimen surface and IR scanner was approximately 120 mm. The influence of the angle between the surface normal and the optical axis of IR scanner on the received signal was determined and is shown in Figure 2. It can be seen that for β values less than approximately 40 degrees, the signal was found to be not significantly dependent on the angle of obliquity.

For comparison purposes a thermistor sensor,with sensitivity of 0.01°C, was secured at the crack tip. The sensor was used to measure the temperature change, and its position on the specimen's surface is shown in Figure 3.

RESULTS

In general, the IR cooling emission obtained from the elastically deformed metals showed them to be below room temperature. In order to measure IR cooling emission more accurately, an IR scanner which is sensitive to a longer wavelength was used. Table 2 and Figure 4 present the comparison of IR cooling emission of elastic deformed metals using both a short wavelength (SW 3-5.6 μm), and a long wavelength (LW 8-14μm) IR scanner. The results indicated that the long wave IR scanner's values were much better than those obtained using the short wave scanner.

Table 2. The comparison of IR cooling emission deformed metals with different wavelength.

	Average change of thermal level units, $\Delta\bar{i}$		
Wavelength range	Aluminum	Carbon steel	Stainless steel
SW 3 - 5.6 μm	0.03	0.04	0.06
LW 8 - 14 μm	0.06	0.09	0.12

The IR Cooling and Heating Emission of a Crack Tip

Figure 5 shows the dynamic process of the IR emission for a carbon steel specimen, with a center cut hole, subjected to tensile loading. Prior to yielding, the IR cooling emission (the dark blue spots in Figure 8) was concentrated in the area of crack tip. The region extended along the crack and radially 45 degrees (Figures 5D and 5E). The maximum cooling value attained over this region was -0.4°C. These IR cooling emission measurements and procedures will be used to predict the stress concentration in the vicinity of the crack tip.

After yielding, the IR heating emission of deformed specimen rises at the crack tip, and this corresponds to the elastic IR cooling emission. Then the characteristic "butterfly" shape of the heating emission was observed extending immediately to the boundary (see Figure 5, image F). In the same figure the point P_T at 31.2 kN on the load versus load-line displacement (LLD) curve corresponds to the inflection point marking the boundary between IR cooling and heating emission regions. This value is identified as the thermoelastic limit load, and is lower than the 0.2% offset engineering yield strength value, 31.8 kN.

The IR cooling emission that existed from the crack tip to the edges of the specimen is shown in Figure 6. The top white horizontal line (dotted) scans the specimen along the crack center, and the bottom white line shows the IR cooling distribution from the crack tip to the edges of test specimen. Comparing image A with image E, it can be seen that the maximum cooling occurred at a crack tip and extended to the boundary of testing specimens.

Figure 7 shows the variation of load P and temperature T versus crack mouth opening displacement (CMOD). A critical point corresponding to the thermoelastic instability was measured using a thermistor sensor placed at the crack tip of each aluminum specimen. The limiting load PT indicates the inflection point from the thermoelastic to irreversible thermoplastic regions. Similar results were found by Sih and Tou (10).

Real-Time Crack Position Determination

Using the above as a foundation, situations of increasing complexity can be explored. For example, Figure 8a shows a photograph of IR cooling emission emanating from a crack tip of a precracked aluminum specimen, and Figure 8b shows the IR heating emission area for the same crack tip. As the passage of the cyclic time increased, a fatigue crack developed. A diagram of the crack front showing the IR cooling and heating areas was developed and is shown in Figure 9. After the crack propagated, a new 45 degree front of IR cooling and heating areas was formed on the surface of fatiguing specimen. This is shown in Figure 10.

The direct current potential drop (DCPD) technique was also used to measure the crack growth of a compact tension specimen during fatigue process (11). In Figure 11 the DCPD data were compared with the measured thermographic values of a crack extension marked by IR cooling and heating emissions. The crack extension values for the thermographic data were in agreement with the DCPD data, and the last thermographic values were same as the optical measured values when the nine point average technique was used (12). The relatively large deviation at crack initiation was due to the low space resolution of thermographic method (0.5 mm by 0.5 mm).

Multiple Phenomenon of IR Cooling Emission

When a specimen containing a crack undergoes loading and unloading below elastic limit, the temperature response is cyclic, that is it rises and lowers with loadings. This response is called as thermoelastic effect. When this occurs, the multiple effects of IR cooling emission are observed, Figure 12. Experimental results, in this same figure, showed that when a metallic specimen was loaded to elastic limit, block 1 through 5, IR cooling emission occurred, and upon unloading, IR heating emission appeared. If the specimen remained in the unloaded condition, see blocks 7a through 11a, for greater than 100 seconds, the specimen was found to cool to a temperature that was lower than the original temperature. Table 3 shows the multiple effect of IR cooling emission in the test metals.

Table 3. The multiple effect of IR cooling emission in the test metals.

Metal	Aluminum	Carbon Steel	Stainless Steel
Elastic stress range (MPa)	17.9 - 259.0	23.4 - 739.2	65.4 - 670.4
RAMP time (s)	100	100	100
Cycle times	12	5	5
Sum of thermal level, $\Sigma\Delta i$	0.63	0.40	0.40
$\lvert i - io \rvert$	0.36	0.30	0.30
ΔT°C	-0.9	-0.8	-0.8

This phenomenon presents an interesting aspect for determining the stress concentration that exists near a crack. In the deformation of metals, the measurement of this IR cooling emission techniques and its multiple effect could be used to detect the stress concentration area as soon as the damage occurs. In most cases, the stress amplitudes that are applied are well below the damage levels, so the thermographic method is nondestructive.
When crack processes are investigated, the stress amplitude during a test is decreased to where the stress levels are not damaging.

CONCLUSIONS

Infrared thermography is a new but reasonably reliable technique for detecting the variation in surface temperature of metals during the deformation process. In particular it shows the following: 1) a long wave length (8 - 14 μm) IR scanner has a higher sensitivity for determining IR cooling and heating emission of deformed metals; 2) the effects of surface obliquity on the received signal level does not significantly depend on the obliquity angle when the angle is less than 50 degrees; 3) IR cooling and heating emissions of a crack tip extends radially about 45 deg from the front of crack and encompasses the stress concentration area created by the crack. Based on this finding, the IR procedure could be used to determine the initiation and propagation of a crack during fatigue process; 4) a critical inflection point was found that separates IR cooling emission from IR heating emission, and also delineates the thermoelastic from the irreversible thermoplastic region that occurs during deformation process; and 5) the metals that were evaluated under slow loading cycles below the elastic limit displayed the multiplied effect of IR cooling emission.

ACKNOWLEDGEMENTS

This project was sponsored by the Federal Railroad Administration, Office of Rail Safety Research, and monitored by Ms. Claire L. Orth, research manager. We gratefully acknowledge the FRA and Ms. Orth's support of this research. In addition, the help of Dr. Richard Grot of the National Engineering Laboratory of NBS, in particular for the use of his infrared equipment is gratefully appreciated.

REFERENCES

1. S.P. Timoshenko and J.N. Godier, "Theory of Elasticity", McGraw - Hill Book Company (1970) p. 476.

2. M.A. Biot, "Thermoelasticity and Irreversible Thermodynamics", J. Appl. Phys. Vol. 2 (1956) pp. 240-283.

3. S.X. Li, Y. Huang, and C.H. Shih, "An Analysis of Heat Field of Metal Sheet During Elastic-Plastic Deformation", International Centre for Theoretical Physics, Technique Report LC/85/179 (1985) Italy.

4. C.E. Bottani, A. Norelli, F. Rossitto, and G. Silva, Met. Italy, Vol 69, (1977) pp. 67.

5. Y. Huang, "The Thermographic Investigation of the Themoelastic Effect in Metals", International Centre for Theoretical Physics, Technical Report IC/85/276 (1985) Italy.

6. B.E. Bottani, G. Caglioti, "Mechanical Instabilities of Metals", Metallurgical Science and Technology, Vol. 2, No. 1, April (1984).

7. G.D. Sih, F.L. Lieu, and C.K. Chao, "Thermal Mechanical Damage of 6061-T6 Aluminum Tensile Specimen", Institute of fracture and Solid Mechanics, Technique Report IFSM-86-146 (1986).

8. Y. Huang, S.X. Li and C.H. Shih, "Investigation of Temperature Fields of Stainless Steel During Deformation", Advances in Fracture Research, Pro. of the 6th Inter. Con. on Fracture, New Delhi, 4-10 De. (1984).

9. Y. May Chang and Richard A. Grot, "Laboratory Design and Test Procedures for Quantitative Evaluation of Infrared Sensors to Assess Thermal Anomalies," National Bureau of Standards, NBSIR 85-3131, (1985).

0. G.C. Sih and D.Y. Tuou, "Irreversibility and Damage of SAFC-40R Steel Specimen in Uniaxial Tension", Theoretical and Applied Fracture Mechanics Vol. 7 (1987), pp. 23-30.

11. Y. Huang, G.H. Hicho, and R.J. Fields, "J-Integral R-Curve Testing of Aluminum Utilizing D.C. Potential Drop and IR Thermographic Techniques", National Bureau of Standards Technical Report, (1987).

12. ASTM E-399, "Standard Test Method for Plane Strain Fracture Toughness of Metallic Materials", American Society for Testing and Materials, Philadelphia (1981).

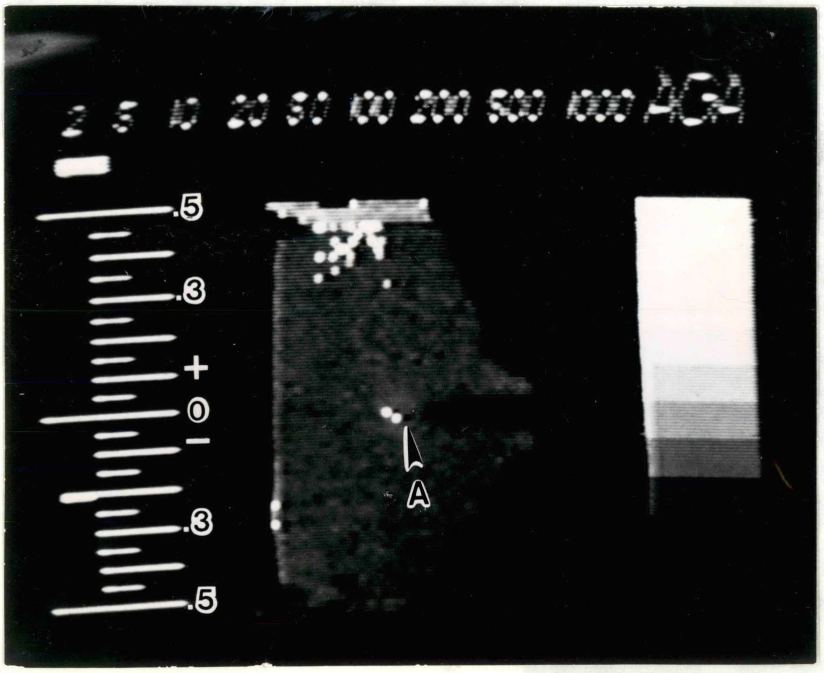


Figure 1. A typical thermogram of a CT specimen taken during a tensile test. The tip of the crack is shown by the arrow A.

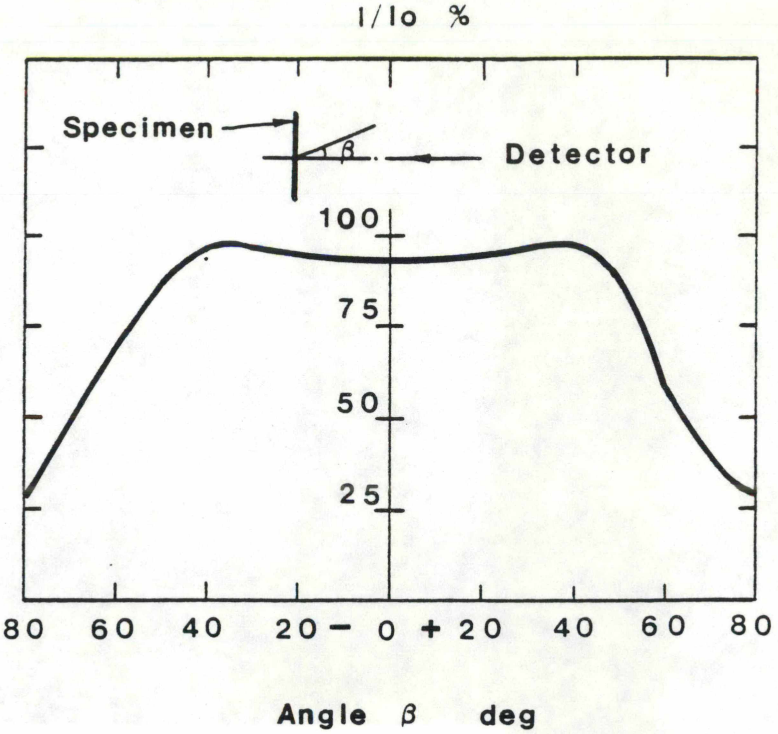


Figure 2. The influence of projected angle to the IR received signal. I/I_o is the ratio of the input to output signal.

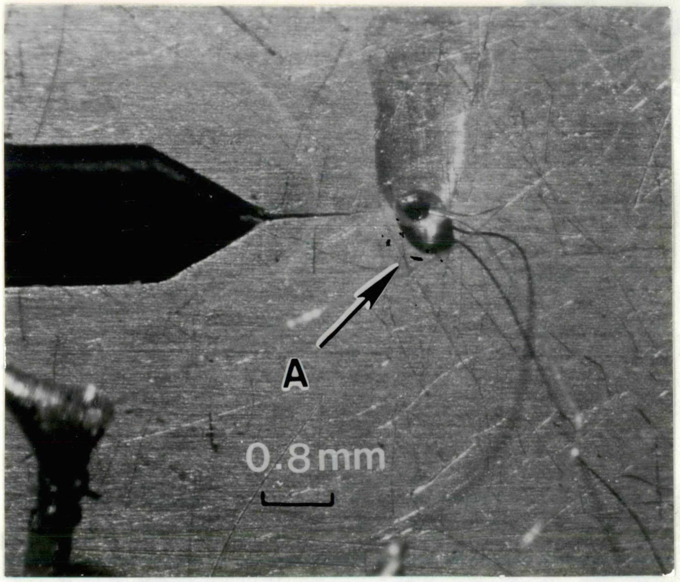


Figure 3. Thermistor sensor positioned at the crack tip. Arrow A points to the thermistor located at the end of the crack.

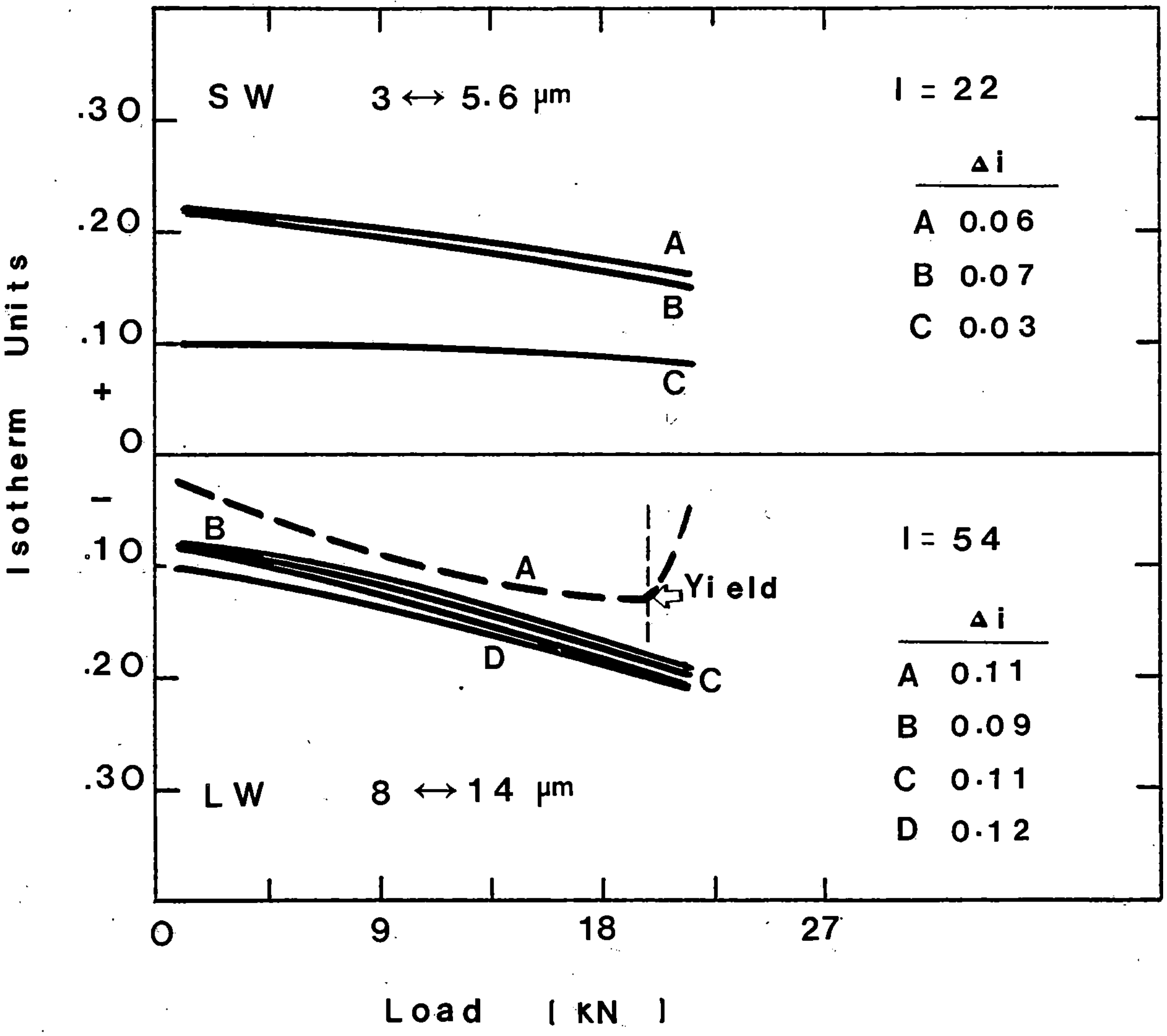


Figure 4. Effect of IR wavelength on received cooling emission signal for a low carbon steel. Curves A,B,C, and D represent the cooling emission for each loading. The other A's,B's,C's, and D's are the contants used to obtain these curves.

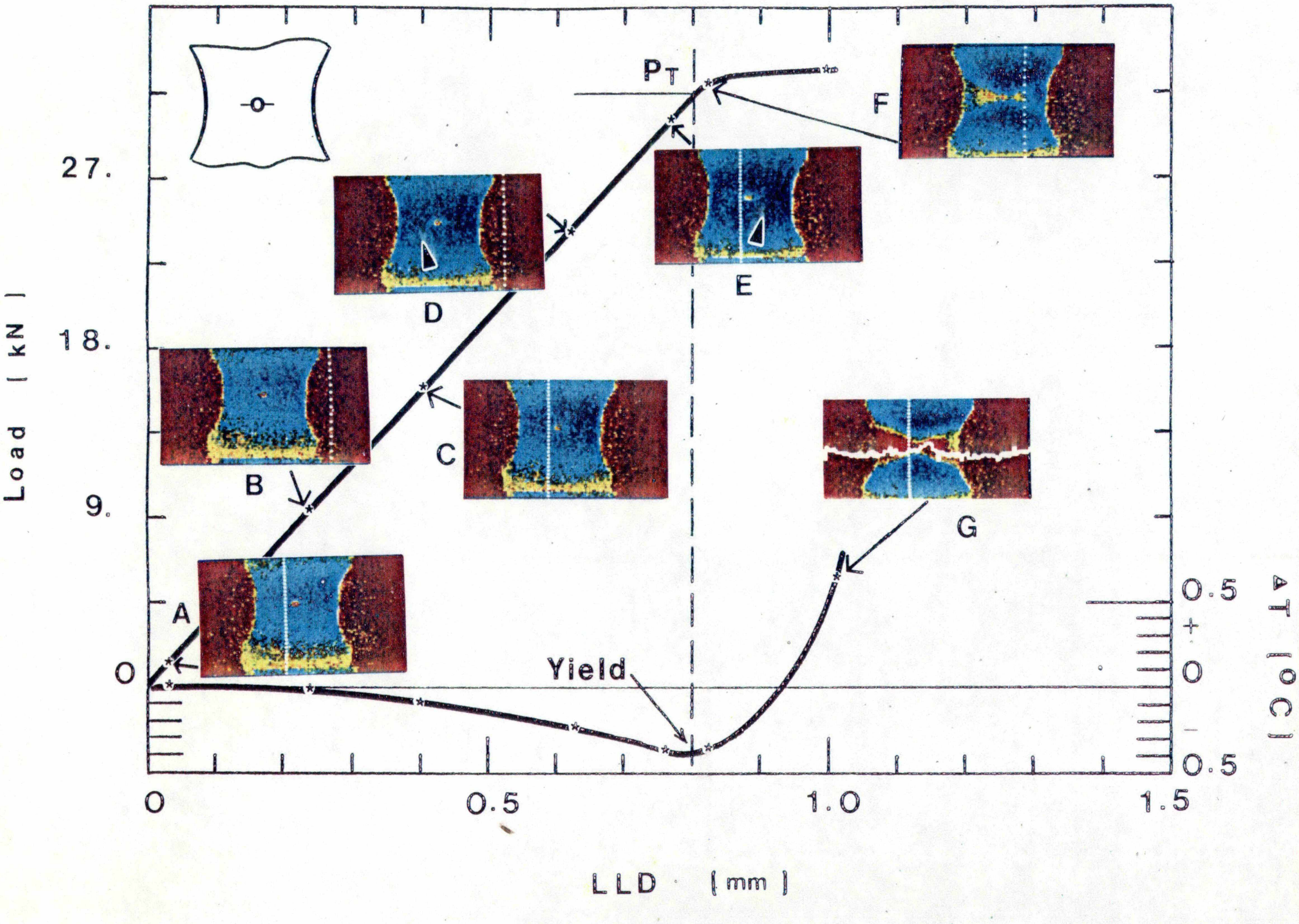


Figure 5. The dynamic process of thermoelastic IR cooling emission of a carbon steel sheet with a center hole with double saw cuts.

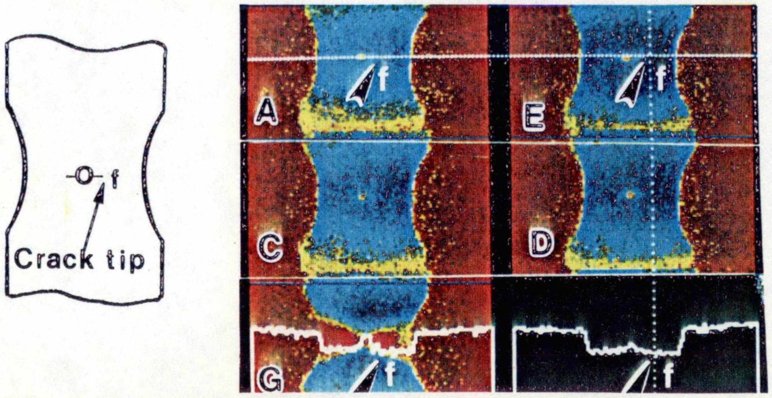


Figure 6. The IR cooling emission distribution along a crack tip to the edges of the specimen.

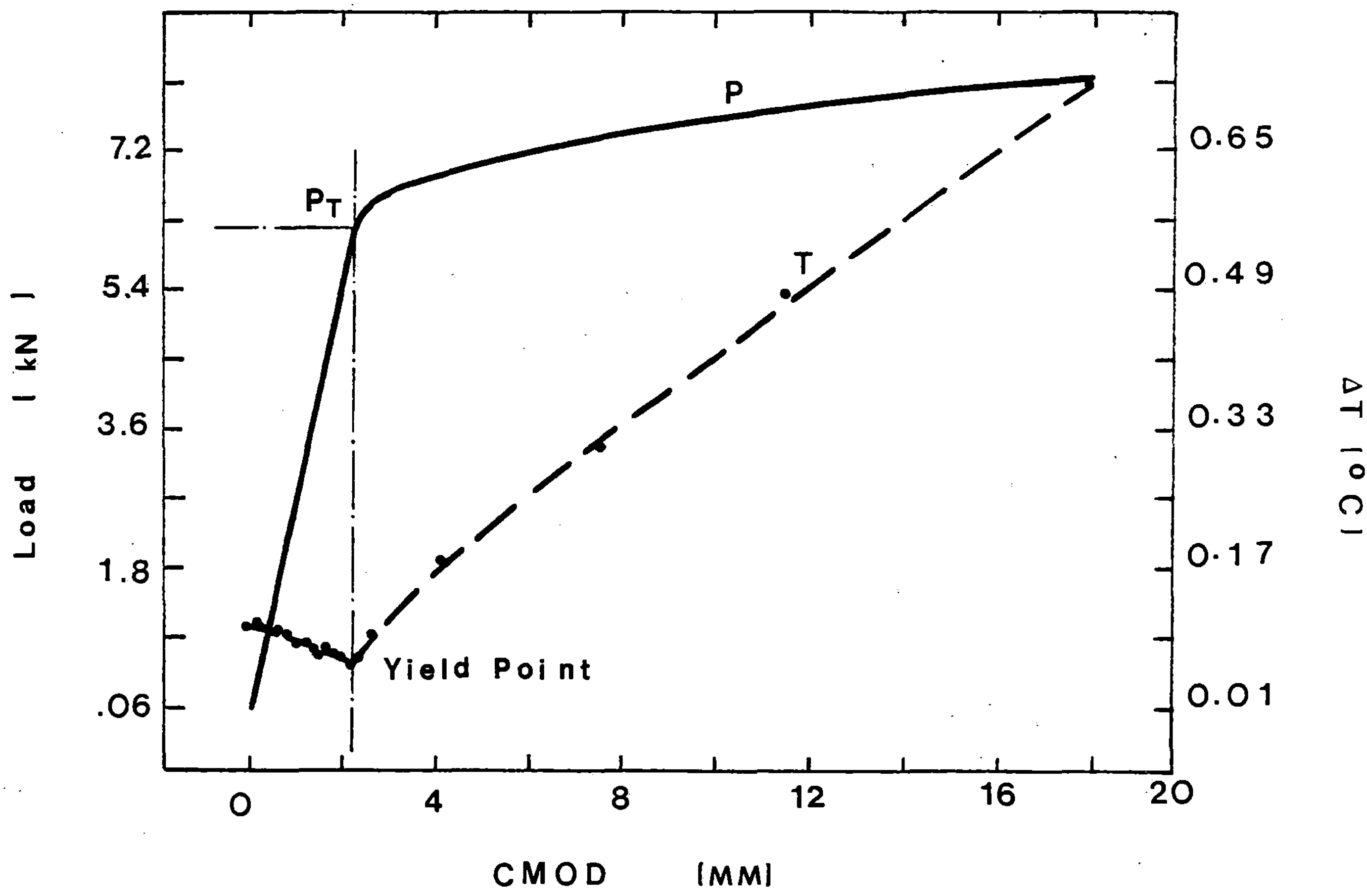


Figure 7. The load P, and temperature T, versus CMOD curves for a CT aluminum specimen.

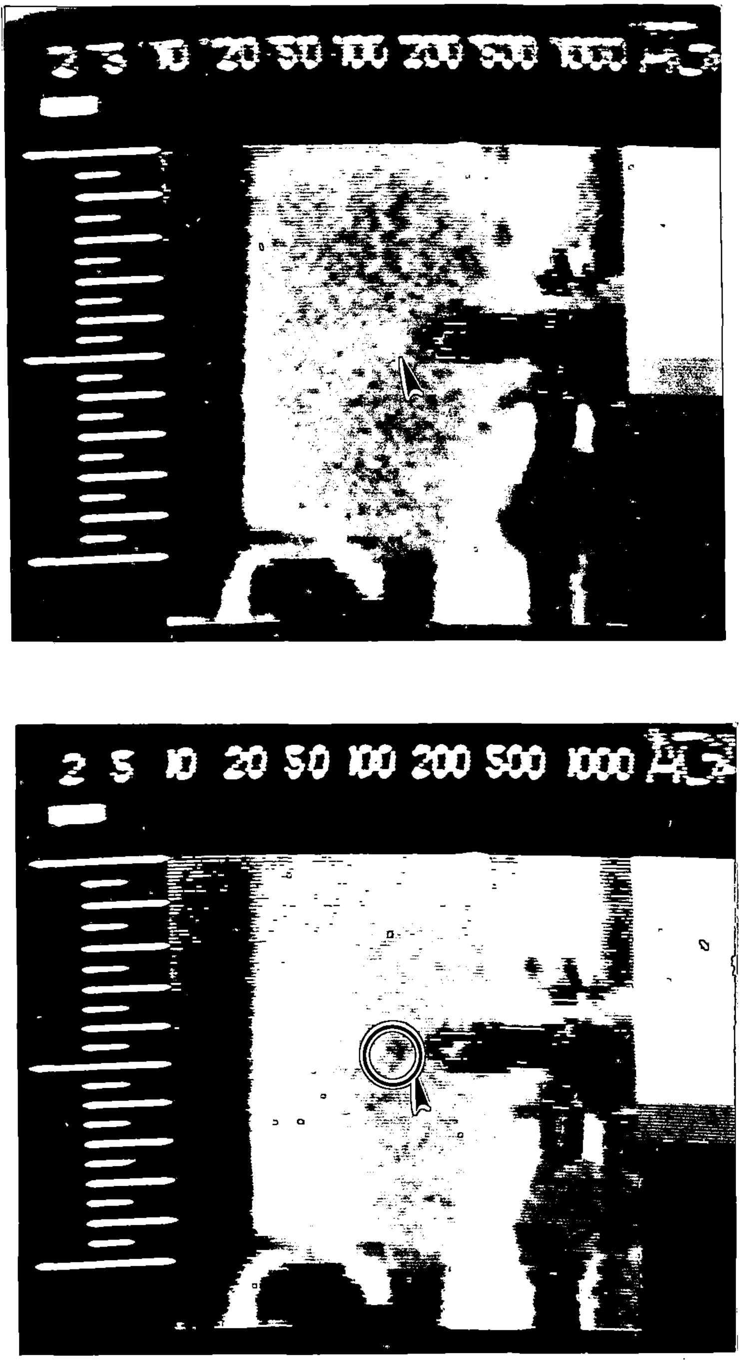


Figure 8. The IR cooling and heating emissions observed near a fatiguing crack tip.

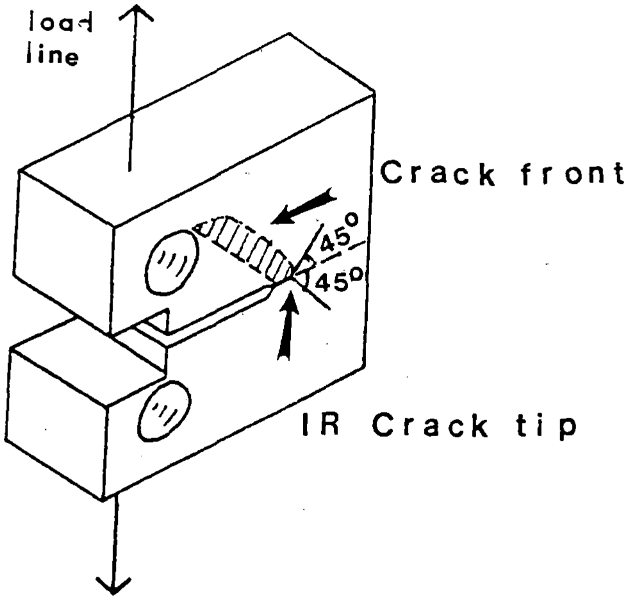
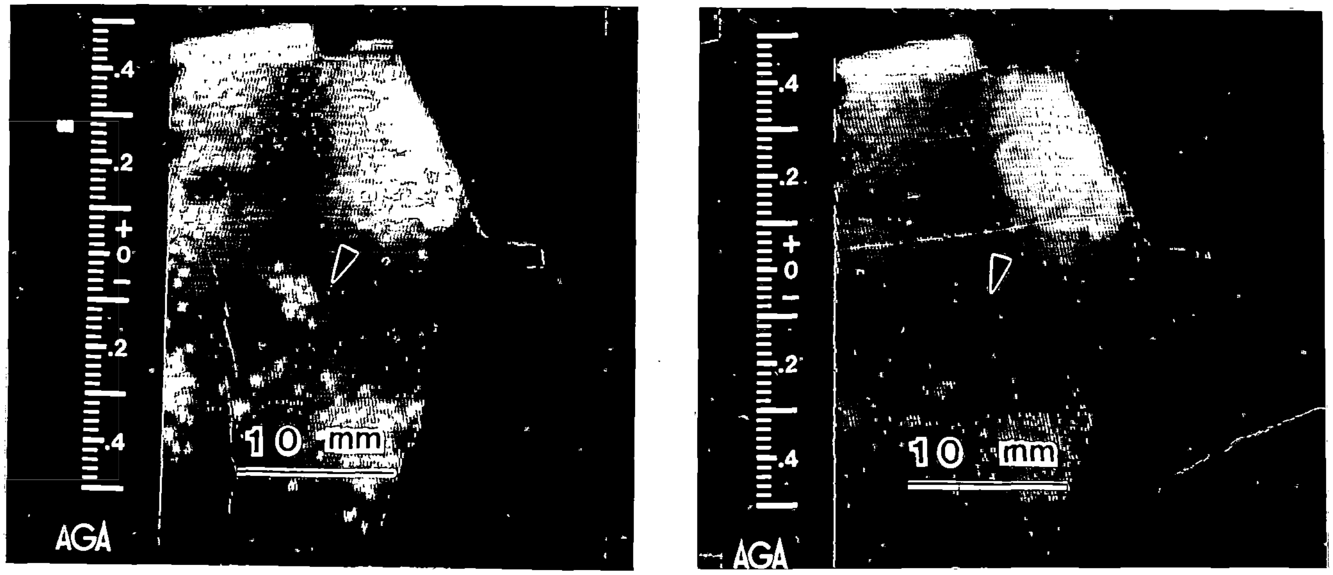


Figure 9. Schematic drawing of the IR cooling and heating emissions observed at the front of the crack.



a) b)

Figure 10. Thermograms showing crack growth during the fatigue process. The fatigue crack, a, and after the crack has propagated, b.

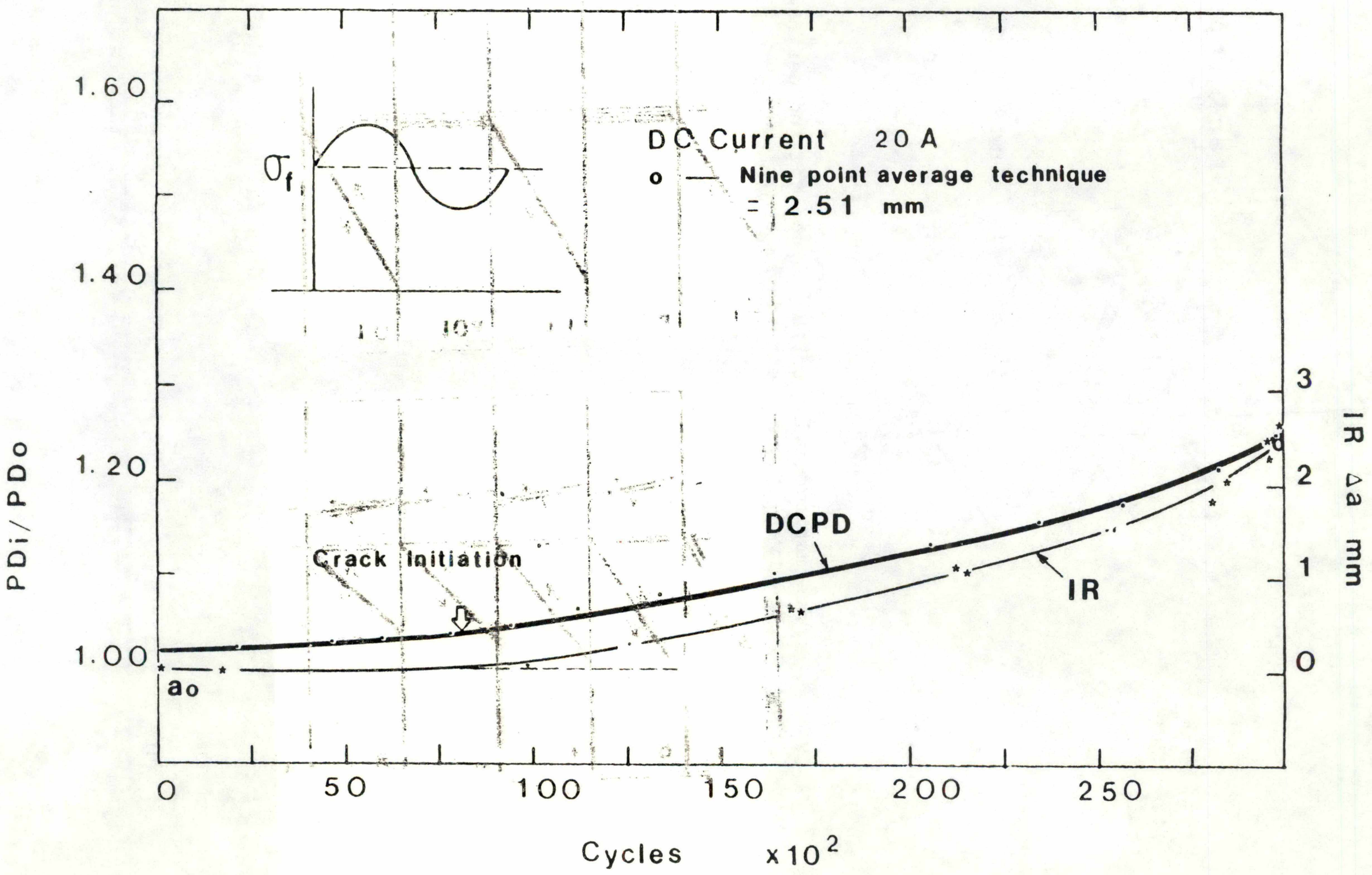


Figure 11. A comparison of the DCPD and IR data with the thermographically measured values of crack extension.

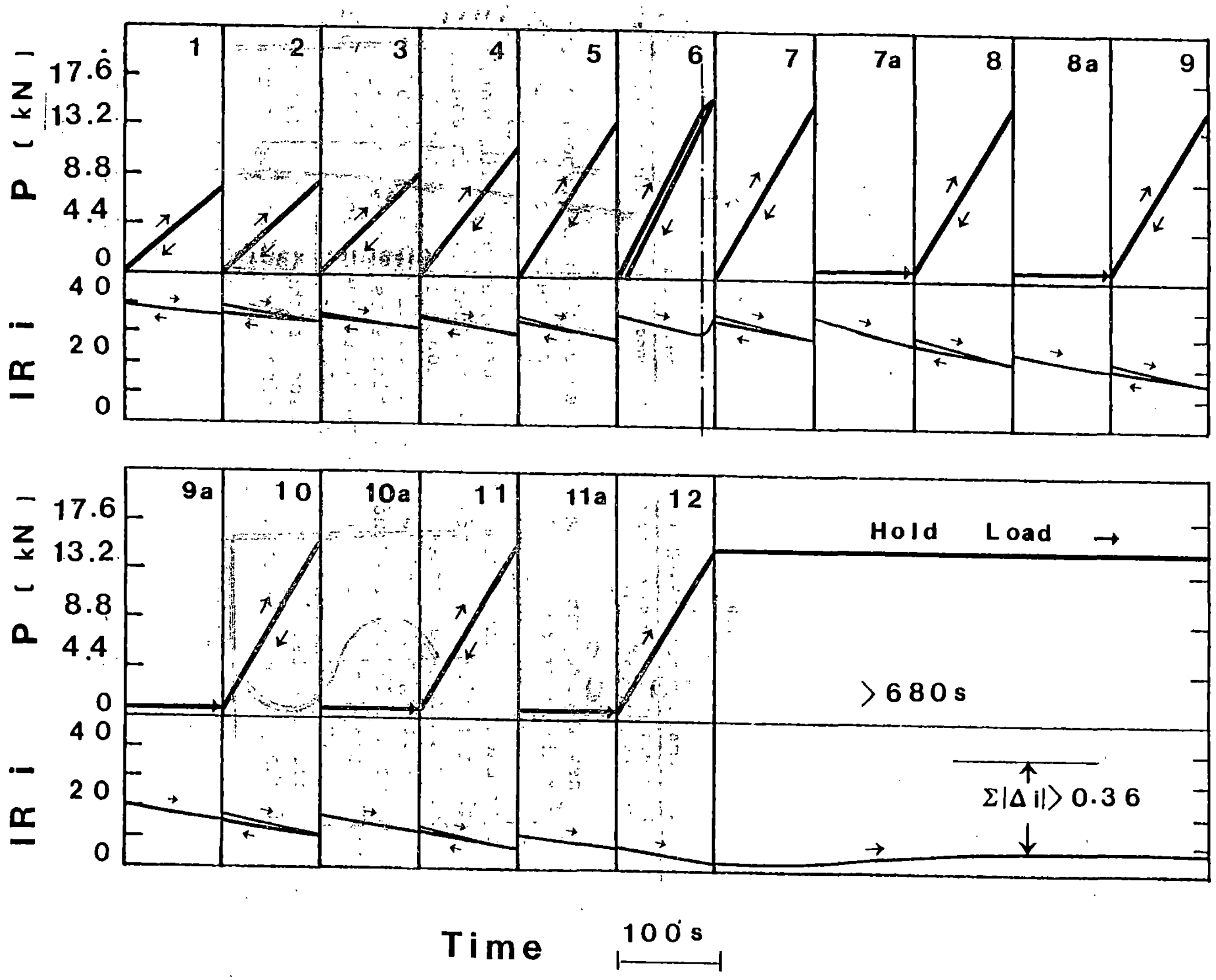


Figure 12. Cumulative effects of IR cooling emissions for an aluminum plate during the elastic loading and unloading cyclic process.

FORM **NBS-114A** (REV.11-84)

U.S. DEPT. OF COMM. BIBLIOGRAPHIC DATA SHEET *(See instructions)*	1. PUBLICATION OR REPORT NO. NBSIR87-3653	2. Performing Organ. Report No.	3. Publication Date

4. TITLE AND SUBTITLE

Infrared Measurements of Cooling and Heating Emissions at a Crack Tip During Tensile and Cyclic Loading

5. AUTHOR(S)

Y. Huang, G. E. Hicho, and R. J. Fields

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
U.S. DEPARTMENT OF COMMERCE
GAITHERSBURG, MD 20899

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Federal Railroad Administration
DOT/FRA OS ORND, Rm. 8305
Washington, D.C. 20595

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

In this paper, a new thermographic method based on the measurement of infrared emission (IR) from the surface of a loaded body has been used to study the cooling and heating in aluminum and steel specimens under tensile and cyclic loading. A typical test procedure using infrared to measure thermographic changes near the crack tip, and the immediate surrounding area are described. In addition, a procedure for determining the stress concentration near the crack tip is also presented. Results are given for thermoelastic cooling phenomenon of metals during the tensile process and IR cooling and IR heating emissions at the crack tip during cyclic loading. Attention is drawn to the multiple phenomenon of IR cooling emission in the received signal as the applied load range increases beyond the elastic limit of both metals. A new application of the IR technique to the determination of the position of crack tip during cyclic loading is also presented.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Aluminum; crack extension; infrared cooling and heating emissions; stress concentration; steel; thermoelastic effect.

13. AVAILABILITY

☐ Unlimited
☒ For Official Distribution. Do Not Release to NTIS
☐ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.
☐ Order From National Technical Information Service (NTIS), Springfield, VA 22161

14. NO. OF PRINTED PAGES

18

15. Price

$9.95

USCOMM-DC 85-6006

Report No. 16 Infrared Measurements of Heating and Cooling Emissions at a Crack Tip During Tensil and Cyclic Loading, 1988
Y Huang, GE Hicho, RJ Fields