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APPLICATION OF INFRARED TECHNIQUE IN RESEARCH OF MECHANICAL PROPERTIES *

Y. Huang **
International Centre for Theoretical Physics, Trieste, Italy
and
C.H. Shih
Institute of Metal Research, Academia Sinica, Shenyang, People's Republic of China.

ABSTRACT

The infrared technique as a new method is more useful for research of materials science. This paper simply describes the techniques of infrared temperature measurement and thermography and provides the experimental data of some metals and alloys during the deformation and the fatigue process by use of the infrared sensing method. It is shown that the conventional tensile data can be correlated with infrared radiational energy change during the tensile pulling. The temperature field of metal during elastic-plastic deformation can be calculated by finite element analysis, and the thermoelastic effect of metal can be shown by thermography. The infrared technique can be used to predict the fatigue damage, monitor their propagations and give the alarm at fracture. Finally, it must be pointed out that the irreversibility of infrared emission of metal can be used as a basis of nondestructive testing.

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** Permanent address: Institute for Metal Research, Academia Sinica, Shenyang, People's Republic of China.

There always occurs infrared radiation in materials when they are at a temperature above absolute zero, and the intensity of radiation is proportional to temperature. The infrared technique has been used for the investigation of deformation of metals and alloys (1), (2). However, the development has been slow because the specific radiation of a metal surface is not sufficiently high and sensitivity of the instruments is limited. The Institute of Metal Research started the application of IR technique to the study of metals about a decade ago. A surface coating material was developed, which is transparent and good for investigation of the change of metal surface during deformation. The specific radiation is so high that it is near to that of graphite, as shown in Fig. 1.

Two types of instruments have been used as infrared temperature sensor, namely a JWH-3 type of domestic construction and an AGA Thermovision 780 imported from Sweden. The sensitivity of JWH-3 is 0.3°C and of the latter is 0.1°C. Fig. 2 is a block diagram of AGA Thermovision 780 system.

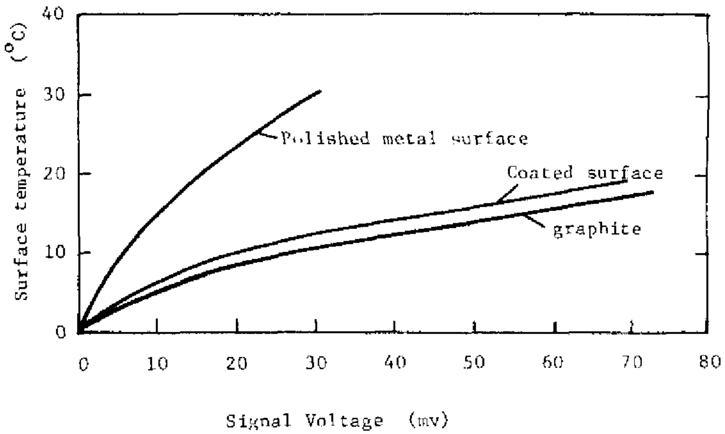


Fig.1 Effect of surface coating on amount of radiation

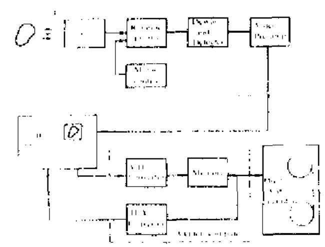


Fig.2 Block diagram of AGA Thermovision 780 system.

Application of infrared technique to research on tensile test

Figure 3 is a stress-strain curve with change of temperature during tensile test of a low carbon steel. Table 1 shows the relationship of maximum temperature rise and mechanical properties of steel. It is indicated that the ultimate temperature rise is essentially proportional to the ductility and thermal conductivity of the material (4). The higher the ductility of the material, the higher will be the maximum temperature rise, as shown by the two carbon steels; and the higher the thermal conductivity, the lower will be the temperature rise, as shown by the low carbon steel and the austenitic stainless steel, in which the ductility as expressed by elongation and reduction of area is different only by about 15%, while the temperature rise is nearly doubled because the thermal conductivity of the latter is about three times higher than that of the former at room temperature.

Temperature change of metal during elastic-plastic deformation can be calculated by finite element analysis by assumptions that it obeys the Kelvin equation and Fourier thermal conduction law (5). The experimental and calculated results of austenitic stainless plates with different notches are shown in Fig.4 and Fig.5.

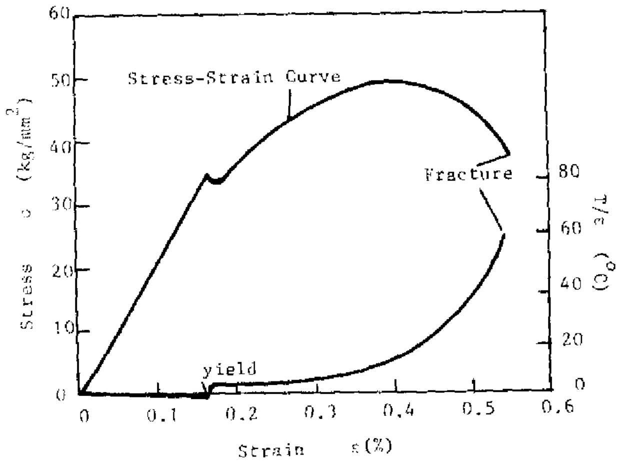


Fig.3 The stress-strain curve and the temperature rise of a low carbon steel.

Table 1. Relationship between the maximum temperature rise and mechanical properties of steel.

steel specimen	max. temp.(°C)	pulling speed (mm/min.)	Handness (Hv)	tensile strength (kg/mm²)	elong. (%)	reduction of area (%)
Low Carbon	24.5	20	174	35.8	31.3	59.0
Med. Carbon	20.3	20	215	70.5	24.2	52.2
Stainless	46.0	20	227	62.8	46.6	69.9

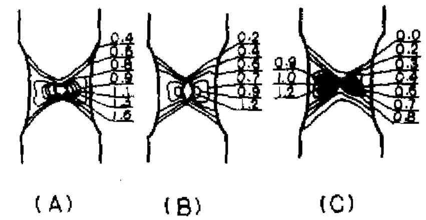


Fig.4 The temperature distributions of thermograms when the plastic zone extended to the boundary.

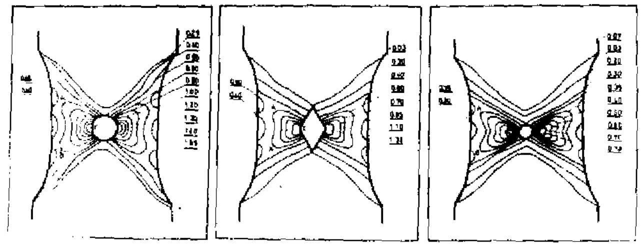


Fig.5 The temperature fields calculated by finite element analysis.

It can be seen that the temperature distributions are quite similar in the above two figures. The rise of temperature is highest with circular notch due to its large area of plastic deformation, and lowest for sharp saw-cut which it is agree with the rule of deformation energy is proportional to the radius of notch of the specimens as shown in Table 2 (6).

Table 2. The Radii and Measured Temperature Rise of Different Notch Roots

Hole form	Circular	Rhombic	Double saw-cuts
Radius (mm)	2.5	0.5	0.1
Rise of temp. (°C)	1.6	1.4	0.8

Fig.6 is the dynamic process of heat field of an austenitic stainless steel plate with double saw-cut notches.

It is worth pointing out that there is a small temperature drop before yield as shown in the figure. This can be confined by calculation based on Kelvin equation as shown in Fig. 7, (7)

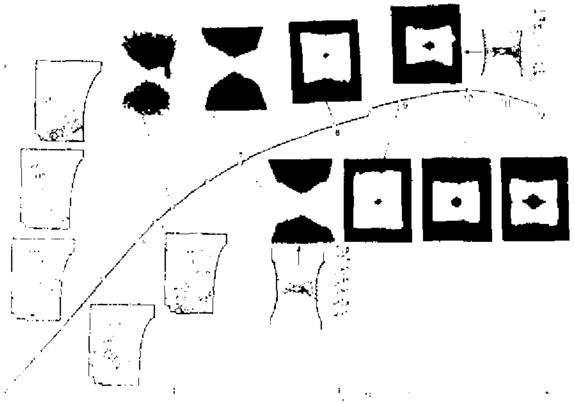


Fig.6 The dynamic process of heat field of a specimen with double saw-cut notch during tensile deformation.

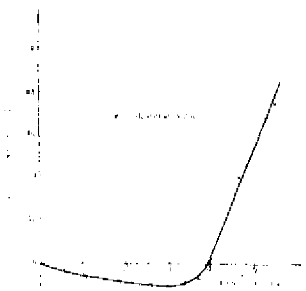


Fig.7 The calculated results of temperature drop during tensile deformation

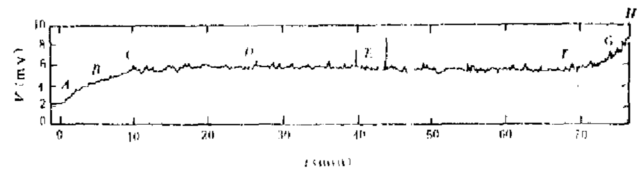
Infared sensing can be developed as a method monitoring fatigue process of metals

Fatigue damage is one of the most destructive processes in the application of metals. However, there is no real-time, noncontact and nondestructive method monitoring the destructive process, especially those parts under high speed revolution are more difficult. The Institute of Metal Research in Shenyang attempted to apply infrared sensing technique to monitor the initiation and propagation of fatigue cracks in metals (8),(9).

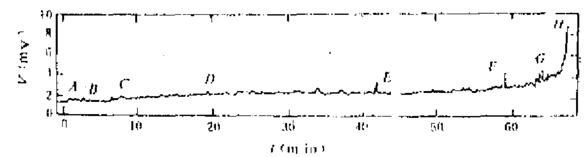
The experiments were on a high speed rotating bending fatigue testing machine (5000 rpm), with a double conical specimen of a minimum section of 7.52 mm at the center. Materials tested were a Cr-Mn-Ni-N high strength stainless steel (924), a Nickel-base superalloy (GH 33) and an Fe-Ni-Cr base superalloy (GH 135). Their mechanical properties and experimental results are shown in Table 3 and Fig.8, respectively. Conclusions can be drawn that the higher the plasticity of the material, the earlier, faster and higher will be the temperature rise, as shown in stainless steel. For those materials with low plasticity, the temperature remains unchanged for a long period, but it rises markedly about ten minutes before the breakage occurs. This is why infrared technique can be used as a method to monitor fatigue cracking.

Table 3. Mechanical Properties of Alloys Used in Experiments

Alloy	Tensile strength (kg/mm^2)	Elong. (%)	Reduction Area (%)	Thermal Cond. ($Cal/cm.s.^{o}C$)	B Value
924	83.3	50	70	0.030	0.020
GH135	119.5	25.6	37	0.026	0.007
GH33	101.9	20	21	0.032	0.003



$S=38kgf/mm^2$ (924)



$S=56\ kgf/mm^2$ (GH 33)

Fig.8 Curves of temperature rise of alloys during fatigue testing.

If we calculated temperature (T) of the specimen with increment of stress ($\Delta S=S-S_0$), the results are shown in Fig.9, in which S_0 is endurance limit and S is the stress at which the test bar is broken after a certain number of cycles, N_f. It is shown that log T and ΔS obey a linear relationship, it can be expressed as

$$T=T_o e^{B\,\Delta S}$$

where T_o is test temperature, B is a constant related to properties of material and testing conditions; B is proportial to the plasticity of the material tested.

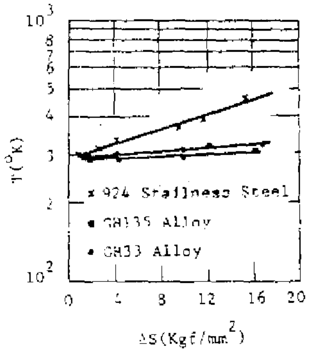


Fig.9 T-ΔS curves of alloys tested.

Figure 10 is the infrared radiation vs crack length under fatigue loading of stainless steel. A is point of start of loading, H is point of fracture. The test bar was removed from the machine for examination once in a while. No crack was observed during AB, and a crack length 0.01 mm occurred after B, and 0.02 mm at D. Length of cracks propagated continuously, to about 1.0 mm at F. The infrared radiation was kept steady until the final stage, at which radiation energy increased drastically, as GH, indicating breakage being approached. The temperature was 75°C in this particular case.

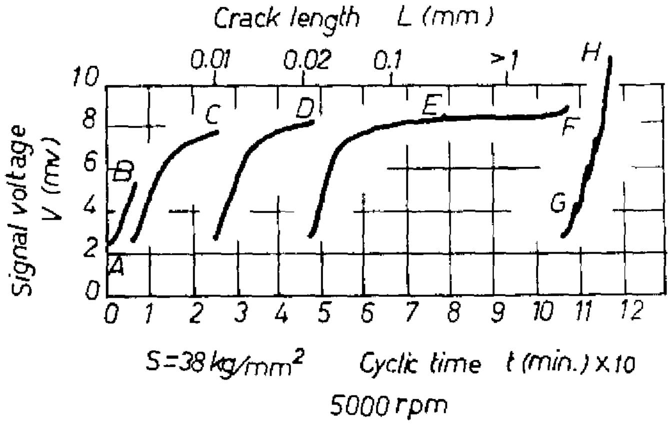


Fig.10 Infrared radiation during fatiguing of stainless steel.

The Irreversibility of Infrared Emission of Metal can be used as a basis of NDT

It has been shown that there is a temperature drop during a tensile test within elastic limit of stainless steel, as shown in Figs.6 and 7. This is called the thermoelastic effect (10). This phenomenon is of theoretical interest in terms of microstructure of the material. Another phenomenon is the irreversible infrared emission during plastic deformation of metals, as shown in Fig. 11 (11). Only a drop of temperature occurs during extension within the elastic limit from 1 to 3, and the more the extension, the lower is the temperature drop; also it will be restored after load is removed. A temperature rise will occur once the extension is beyond the elastic limit as in 4. Temperature will be back again when load is removed. If load is applied again, as 5, temperature drops continuously until the previous point of maximum deformation, and then temperature rises with further plastic deformation, as 6, etc. Hence, it can be concluded that a temperature rise is always associated with plastic deformation and this is irreversible as in the Kaiser effect of acoustic emission (12). The Kaiser effect is the theoretical base for acoustic emission which can be used as a method of nondestructive testing, and therefore, infrared technique can also be used as a method of NDT.

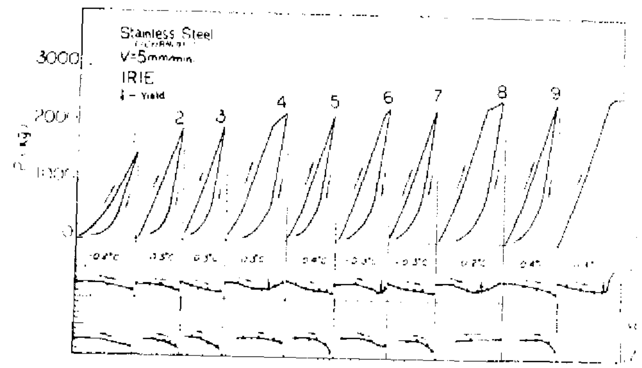


Fig.11 The irreversible phenomenon of infrared radiation of stainless steel during tensile testing.

Figure 12 shows the full history of extension deformation and temperature variation of a stainless steel bar, it is shown that the maximum temperature drop is -0.3°C, and the maximum temperature rise at point of fracture is 94°C.

Low carbon steel and martensitic stainless steel (1Cr13) are quite similar to that of austenitic steel. However, the temperature drop is more pronounced in titanium alloys (as Ti6Al4V), which is -0.8°C, the temperature rise at point of the fracture is much lower (7.6°C) due to its poor plasticity. These facts may imply that temperature drop is closely related to modulus of elasticity of material instead of its crystal structure.

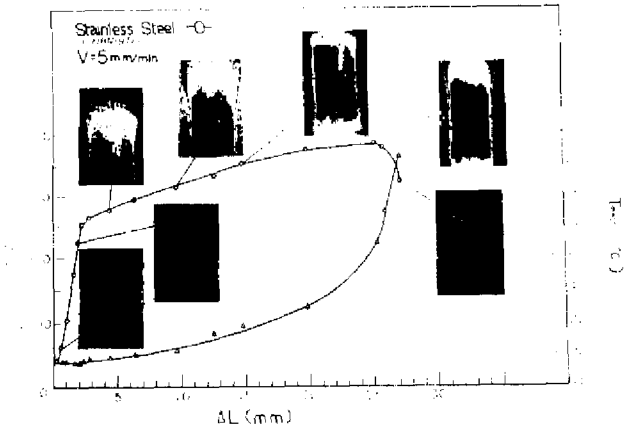


Fig.12 Temperature changes vs tensile deformation of a stainless steel

Conclusion

Various thermal phenomena of metals and alloys under applied loading are a most important research subject. The application of infrared techniques in materials science made it possible to develop a method which works in real time, avoids contact and non-destructive, and also to examine the variation in microstructure of the material. This transient type of heat release can be large and easily observed and can be used as the basis of a method to detect damage development. In the field of materials science, the application of infrared techniques is still in the developmental stage, and work at the Institute of Metal Research will continue.

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REFERENCES

1. J.K. Charles, J.E. Francis and F.F. Appl. Proceedings of the Second Conference on Mechanical Behaviour of Materials, Part A. (1976) p. 817.

2. D.K. Wilburn, Materials Evaluation, Vol. 35, No. 3 (1977) p.3.

3. Y. Huang, J. Xu and S.R. Lin, Chinese Journal of Laser and Infrared No. 7 (1981) p. 8.

4. Y. Huang, J. Xu and C.H. Shih, Materials Evaluation, Vol. 38, no. 12, (1980).

5. S.X. Li, Y. Huang and C.H. Shih, Acta Metallurgica Sinica, Vol 21, No. 1 (1985) p. 7.

6. Y. Huang, S.X. Li and C.H. Shih, Advances in Fracture Research, Proceedings of the 6th International Conference on Fracture, New Delhi, 4-10 December (1984), p. 2325.

7. C.E. Bottani and G.Caglioti, Metallurgical Science and Technology, Vol. 2, No. 1 (1984).

8. Y. Huang, S.X. Li and S.E. Lin, Chinese Journal of Infrared Research, Vol. 3, No. 1 (1984) p. 43.

9. Y. Huang, S.X. Li and C.H. Shih, Materials Evaluation, Vol. 42, No. 8 (1984) p. 1020.

10. G. Caglioti, The Thermoelastic Effect, Statistical Mechanics and Thermodynamic of the Elastic Deformation in Procs. of the Varenna School of Physics "E. Fermi", cit. p. 1-34.

11. Y. Huang et al. unpublished results (1984-1985).

12. H.L. Dunegan and C.A. Tatro, Passive Pressure Transducer Utilizing Acoustic Emission, Rev. Sci. Instrum, Vol. 38, No. 8 (1967), p. 1145.