Application of infra-red techniques to research on mechanical properties

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Abstract

Infra-red techniques can serve as a new tool, particularly useful in materials science research work. This paper describes the available techniques for infra-red temperature measurement and thermography, and provides experimental data for some metals and alloys, obtained by infra-red sensing during deformation and fatigue processes. It is shown that conventional tensile data can be correlated with the change in infra-red radiation which occurs during tensile stressing. The temperature field of a metal undergoing elastic-plastic deformation can be calculated using finite element analysis; on the other hand, the thermoelastic effect on the metal can be shown by thermography. Infra-red techniques can be used to predict fatigue damage, to monitor crack propagation and to give the alarm in the event of fracture. Finally, the irreversibility of the infra-red emission from the metal can be used as a basis for non-destructive testing.

Riassunto

Applicazione delle tecniche infrarosso in ricerche sulle caratteristiche meccaniche

Le tecniche infrarosso possono essere utilizzate come un nuovo strumento di ricerca nel campo della scienza dei materiali. L'articolo descrive le tecniche infrarosso di misura della temperatura e della termografia. Vengono inoltre forniti i dati sperimentali relativi ad alcune leghe metalliche, ricavati mediante misure infrarosso durante la deformazione e l'affaticamento dei metalli. Si mette in luce che le caratteristiche tensili convenzionali possono essere correlate con i cambiamenti nell'emissione di radiazioni infrarosse sotto l'azione di sollecitazioni tensili crescenti. Il campo di temperatura di un metallo sottoposto a deformazione elastoplastica può essere calcolato con la tecnica degli elementi finiti, mentre l'effetto termoelastico nel metallo può essere desunto dalla termografia.

Le tecniche infrarosso possono essere applicate per predire il danneggiamento di fatica, per controllare la propagazione delle cricche e per segnalare l'imminenza della frattura.

Infine, l'irreversibilità del processo che porta all'emissione infrarosso da parte del metallo può essere utilizzata come base di controllo non distruttivo.

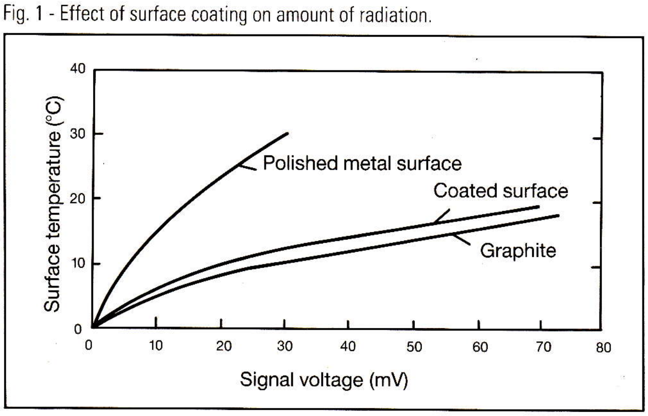
Introduction

All materials at temperatures above absolute zero radiate infra-red rays, the intensity of the radiation being proportional to the temperature. Infra-red techniques have already been used for investigating the deformation behaviour of metals and alloys (1, 2), but development has been slow, because the specific radiation from a metal surface is not high enough, and the sensitivity of our instruments is limited.

The Shenyang Institute of Metal Research started applying IR techniques to the study of metals about a decade ago. A transparent coating was developed which was suitable for investigating changes in the surfaces of metals undergoing deformation (3). Its specific radiation was so high that it approached that of graphite as shown in Fig. 1.

Two types of instrument were used as infra-red temperature sensor, namely a JWH-3 type, made in the People's Republic of China, and an AGA Thermovision 780, imported from Sweden. Sensitivity of the former is 0.3°C and of the latter 0.1°C. Fig. 2 presents a block diagram of the AGA system.

Fig. 1 - Effect of surface coating on amount of radiation.



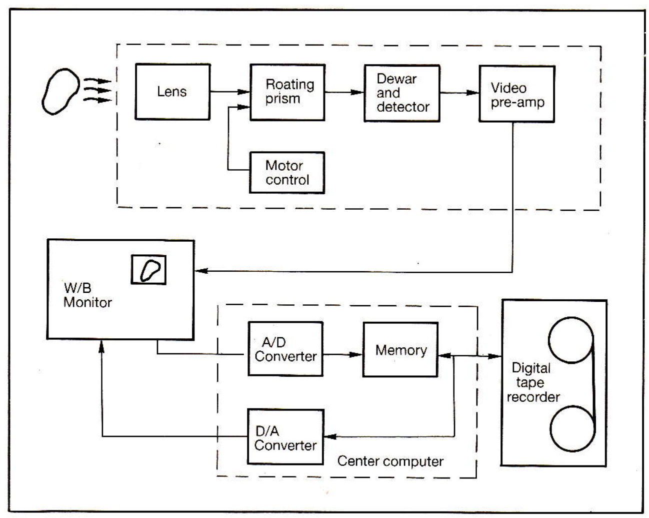


Fig. 2 - Block diagram of AGA Thermovision 780 system.

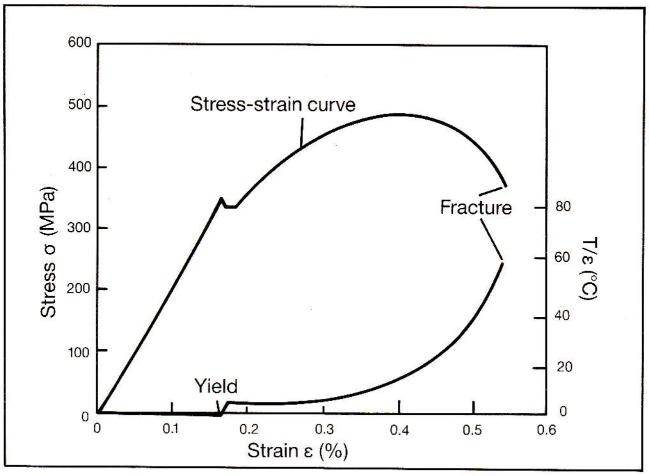
Application of infra-red techniques to tensile testing research

Fig. 3 presents a stress/strain curve of temperature change during tensile testing of a low-carbon steel. Table 1 gives the relationship between maximum temperature rise and the mechanical properties of the steel. It shows 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;

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

Steel specimen	Max. temperature (°C)	Pulling speed (mm/min)	Hardness (HV)	Tensile strength (MPa)	Elong. (%)	Reduction of area (%)
Low carbon	24.5	20	174	358	31.3	59.0
Med. carbon	20.3	20	215	705	24.2	52.2
Stainless	46.0	20	227	628	46.6	69.9

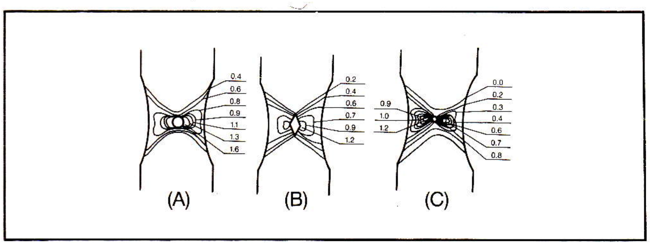
Fig. 3 - The stress-strain curve and the temperature rise of a low carbon steel.



and the higher the thermal conductivity, the lower will be the temperature rise. In a low-carbon steel and in an austenitic stainless steel, for example, the ductility as expressed by elongation and reduction of area, differs only by about 15%, while the temperature rise almost doubles, because the thermal conductivity of the latter is about three times that of the former, at room temperature.

The change in the temperature of a metal during

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



elastic-plastic deformation can be calculated by finite element analysis on the assumption that it obeys Kelvin's equation and Fourier's law of thermal conductivity (5). Experimental and calculated results for austenitic stainless steel plates with different notches are shown in Figs. 4 and 5.

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

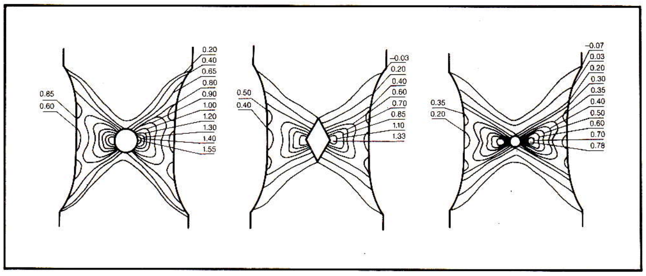


Fig. 6 - The dynamic process of heat field of a specimen with double saw-cut notch during tensile deformation.

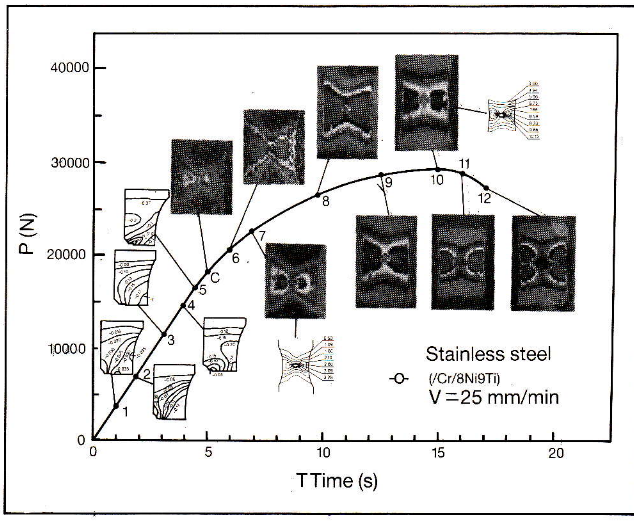


TABLE 2 - The radii and measured temperature rise of different notch roots

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

It can be seen that temperature distribution patterns are very similar in these two figures. The temperature rise is highest with the circular notch, due to the large area of plastic deformation, and lowest for the sharp saw-cut, which agrees with the rule that the deformation energy is proportional to the notch radius of the specimen, as shown in Table 2 (6).
Fig. 6 illustrates the dynamic process of the heat field of an austenitic stainless steel plate with double saw-cut notches. It is worth noting that the temperature drops slightly before rupture, as shown in the figure. This can be confirmed by a calculation based on Kelvin's equation, as shown in Fig. 7 (7).

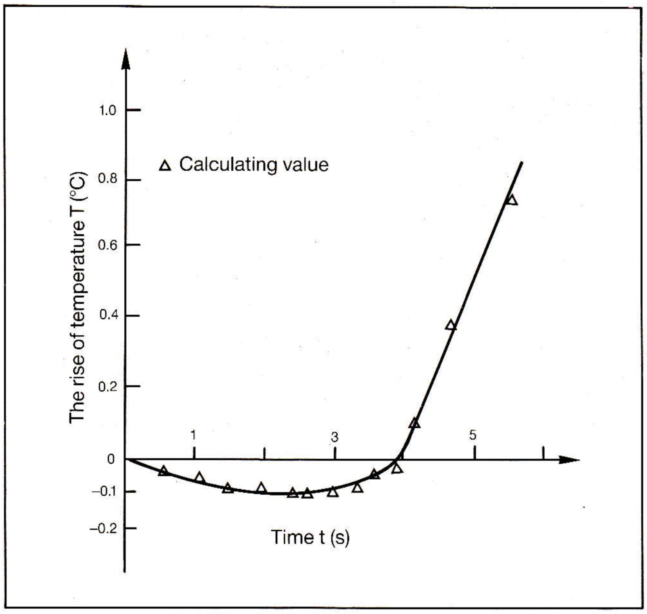


Fig. 7 - The calculated results of temperature drop during tensile deformation.

Development of infra-red sensing as a method of monitoring the fatigue process in metals

Fatigue damage is one of the most destructive processes when it affects metals in structural applications, and there is no reliable means of non-contact, non destructive monitoring of its process. In particular, parts rotating at high velocity are most difficult to examine. The Shenyang Institute of Metal Research has made an attempt at using an infra-red sensing technique to monitor the initiation and propagation of fatigue cracks in metals (8, 9).
The experiment utilized a high-speed rotating bending fatigue testing machine (5000 rpm.), with a double-conical specimen having a minimum section of 7.52 mm at the centre. The materials tested were a Cr-Mn-Ni-N high-strength stainless steel (924), a nickel-based superalloy (GH 33) and an Fe-Ni-Cr-based superalloy (GH 135). Their mechanical properties and the results of the experiment are given in Table 3 and Fig. 8, respectively.

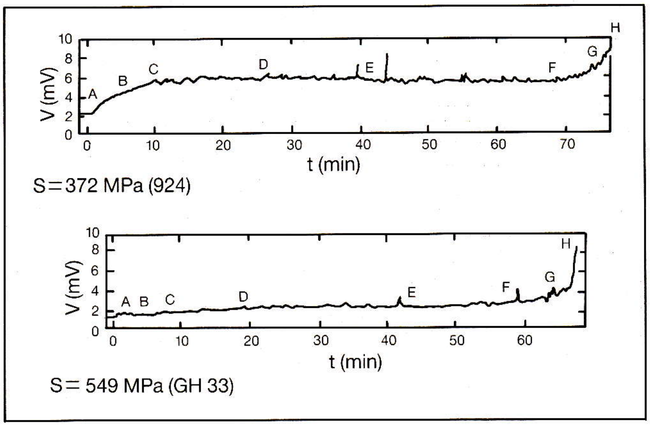


Fig. 8 - Curves of temperature rise of alloys during fatigue testing.

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 infra-red techniques can be used as a method to monitor fatigue cracking.
If we calculate the temperature of the specimen (T) with an increase of stress ($\Delta S = S\text{-}S_0$), the results are as shown in Fig. 9, where S_0 is the endurance limit and

TABLE 3 - Mechanical properties of alloys used in experiments

Alloy	Tensile strength (MPa)	Elong. (%)	Reduction area (%)	Thermal cond. [J/(ms°C)]	B Value
924	833	50	70	16	0.020
GH135	1195	25.6	37	12	0.007
GH33	1019	20	21	15	0.003

S the stress at which the bar broke after a certain number of cycles, Nf. Log T and ΔS are seen to obey a linear relationship, expressed as:

$$T = T_0 e^{B \Delta S}$$

where T is the test temperature, B is a constant related to the properties of the material and the test conditions; B is proportional to the plasticity of the test material.
Fig. 10 represents the infra-red radiation vs the crack length with fatigue loading of stainless steel. A is the point at which loading started and H is the point of fracture.
The test bar was periodically removed from the machine for examinaton. No cracking was observed during AB; a crack 0.01 mm long occurred after B, measuring 0.02 mm long at D.
The cracks propagated continuosly, to about 1.0 mm long at F. The infra-red radiation was maintained steady until the final stage, at which the radiation energy increased dramatically as GH approached, indicating rupture. In this particular case, the temperature at rupture was 75°C.

Fig. 9 - T-ΔS curves of alloys tested.

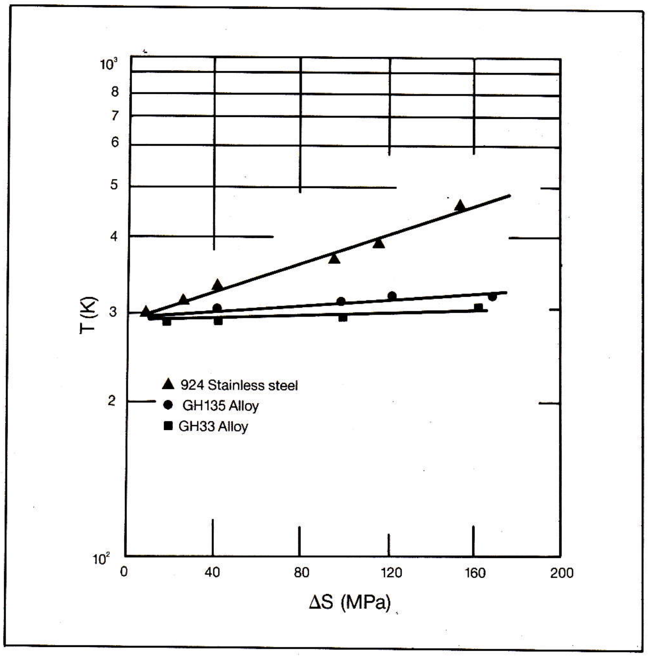
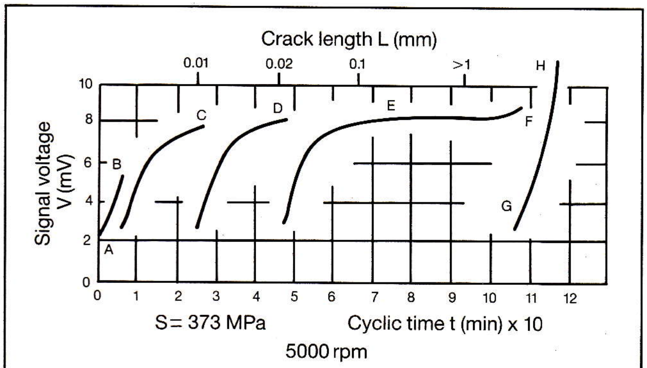


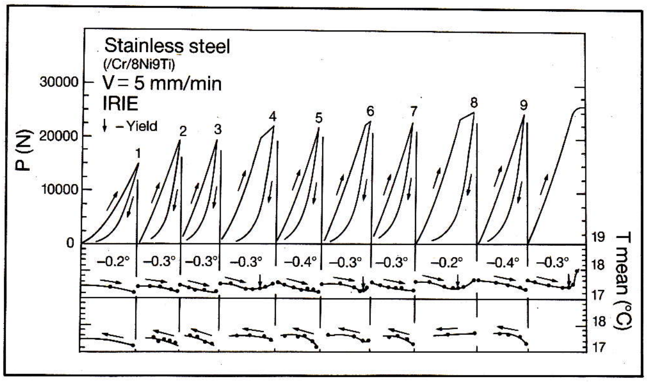
Fig. 10 - Infrared radiation during fatiguing of stainless steel.



Irreversibility of infra-red emission from metals used as a basis for NDT

As it has been shown in Figs. 6 and 7, the temperature drops during a tensile test within the elastic limit of stainless steel. This phenomenon, called the thermo-elastic effect (10), is of theoretical interest as regards the microstructure of the material. Another phenomenon is the irreversible infra-red emission during the plastic deformation of metals, as shown in Fig. 11 (11). A drop in temperature occurs during elongation within the elastic limit from 1 to 3, and the greater the elongation, the higher the drop in temperature; it is restored as soon as the load is removed. The temperature will rise once the extension is beyond the elastic limit, as in 4. The temperature will be restored when the load is removed. If the load is reapplied, as in 5, the temperature drops continuously, down to the previous point of maximum deformation; it rises then with further plastic deformation, as in 6, etc. Hence, we can conclude that a temperature rise is always associated with plastic deformation, which is irreversible, as in the Kaiser effect of acoustic emission (12). The Kaiser effect is the theoretical basis for acoustic emission which can be used as a method of non-destructive testing. Therefore, the infra-red techniques can also be used as a method of NDT.
Fig. 12 shows the whole history of extension deformation and temperature variation of a stainless steel bar. It shows that the maximum temperature drop

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



is – 0.3°C and the maximum temperature rise at the point of fracture is 94°C.
Low-carbon steels and martensitic stainless steels (e.g. 1 Cr 13) show behaviour patterns very like that of austenitic steel. However, the temperature drop is more pronounced with titanium alloys (such as Ti 6 Al 4 V), which is – 0.8°C; the temperature rise at the point of fracture is much lower (7.6°C) due to their poor plasticity. These facts suggest that temperature drop is closely related to the modulus of elasticity of the material, rather than its crystalline structure.

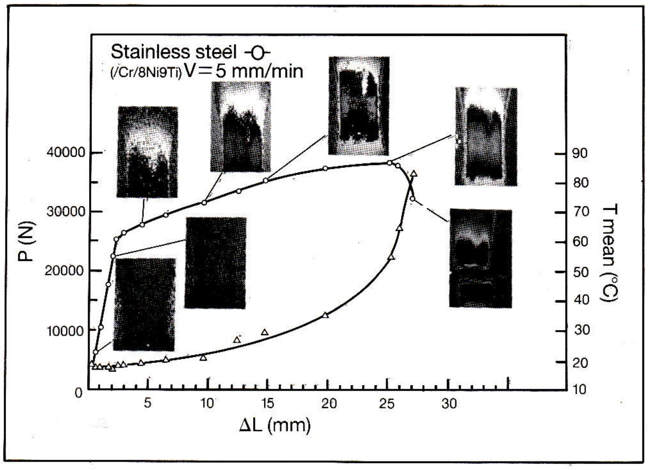


Fig. 12 - Temperature changes vs/tensile deformation of a stainless steel.

Conclusion

The different thermal phenomena exhibited by metals and alloys under stress are a most important research subject.
The application of infra-red techniques in materials science has made it possible to develop a method which works in real time, avoids contact and is non destructive. This transient type of heat release can be large, easily observed and can be used as the basis of a method of detecting the development of damage. In the field of materials science, the use of infra-red techniques is still in the development stage, and work at the Shenyang Institute of Metals Research will continue.

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