INVESTIGATION OF TEMPERATURE FIELDS OF STAINLESS STEEL DURING DEFORMATION

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ABSTRACT

In this study, AGA Thermovition 780 System has been used to give a dynamical pattern of the temperature fields of stainless steel plate during tensile deformation. The heat fields of elastic-plastic deformation were calculated by using the finite element analysis. It is shown that the results of calculation agree well with the measured temperature distribution of the notched specimens of stainless steel.

The drop in temperature before yielding is a very interesting phenomenon, and it disappears as soon as yielding sets in. There is an avalanche of infrared emission of energy as the test specimen approaches fracture.

The results indicate that this method is valuable both in the dynamical study of fracture and in nondestructive testing.

KEYWORDS

Negative temperature effect; the deformation heat fields; finite element analysis; dynamical pattern of fracture.

INTRODUCTION

In metallic materials energy is generated during deformation and fracture. Most of this energy appears in form of heat, which is dissipated from specimen by conduction, convection and radiation. However, previous works in this area could not give clear picture of dynamical pattern of deformation due to limitations of experimental technique.

Recent results (Wilburen, 1977; Charles, 1978; Henneke, 1979; Huang, 1980) indicate that the application of infrared technique for material study has been established. The thermography using scanning infrared camera (Charles, 1976; Williams, 1977) has been employed to obtain accurate surface temperature distribution for the deformed metals and composite materials.

In this paper an attempt is made on monitoring the temperature fields of stainless steel during process of deformation by use of AGA Thermovision 780 System and to calculate the dynamical pattern of deformation by use of finite element analysis.

FINITE ELEMENT ANALYSIS OF ELASTIC-PLASTIC DEFORMATION HEAT FIELDS OF STAINLESS STEEL

It has been known that Kelvin equation can describe the distribution of temperature during deformation of solid substances (Fung, 1965), that is,

$$\frac{\partial}{\partial X_i}\left(K_{ij}\frac{\partial T}{\partial X_j}\right) = \rho C_v\frac{\partial T}{\partial t} + T\beta_{ij}\frac{\partial \varepsilon_{ij}}{\partial t} \qquad (1)$$

$(i, j, = 1, 2, 3)$

Assuming that Fourier thermal conduction law is valid with a small amount of elastic-plastic deformation, an unsteady heat conduction equation can be written as:

$$\rho C_v\frac{\partial T}{\partial t} = \frac{\partial}{\partial X_i}\left(K_{ij}\frac{\partial T}{\partial X_j}\right) + \dot{Q} \qquad (2)$$

Where $\dot{Q} = \dot{Q}_e + \dot{Q}_p$ is the rate of heat generation per unit volume and $\dot{Q}_e$ and $\dot{Q}_p$ are rates of heat generation per volume during elastic and plastic deformation respectively. From equation (1),

$$\dot{Q}_e = -T\beta_{ij}\frac{\partial \varepsilon_{ij}}{\partial t} \quad \text{and} \quad \dot{Q}_p = \gamma\bar{\sigma}\dot{\bar{\varepsilon}}_p \qquad (3)$$

Where $\bar{\sigma}$ is equivalent stress; $\dot{\bar{\varepsilon}}_p$ the equivalent rate of plastic deformation and γ the coefficient of plastic work and heat conversion (here $\gamma = 0.95$) (Nabarro, 1967).

In order to calculate the stress-strain field, finite element analysis with the application of Mises yield criterion and the Prandl-Reuss eigenequation of incremental theory has been used, and the triangular subdivided linear displacement model and variable stiffness method to calculate the elastic-plastic deformation field have been adapted (Li and Colleagues, 1982).

Load P and its increament ΔP related to time t and Δt can be obtained by using load-time curve during process of deformation. The stress-strain field at each load level and each time interval can be calculated step by step, then, $\dot{Q}_p$ and $\dot{Q}_e$ can be determined.

Calculation of temperature distribution is similar to that of elastic-plastic deformation. The area around arbitrary node i, which is surrounded by the mid side nodes and form centers is regarded as an area of node i, and the node temperature is considered as that of the area. Heat source, $\dot{Q}\Delta t\Delta v$ can be calculated, and then the thermal conduction and heat dissipated from the boundaries were considered. Combine heat balance principle, the difference equations of inside-node and boundnode can be obtained.

The hidden difference equation of inside node can be written as:

$$\begin{aligned}&\left(\sum_e C_v\rho A\right)T_{i,t} + \frac{3}{4}\Delta t\sum_e\frac{K}{A}\left[(b_i^2+c_i^2)T_{i,t}+(b_ib_j+c_ic_j)T_{j,t}\right.\\&\left.+(b_ib_m+c_ic_m)T_{m,t}\right] + 2\Delta t\left(\sum_e\beta_o A\right)T_{i,t} = \left(\sum_e C_v\rho A\right)T_{i,t-\Delta t}\\&+\sum_e\gamma\bar{\sigma}\Delta\dot{\bar{\varepsilon}}_p A+\sum_e(-T_i\beta_{uv}\Delta\varepsilon_{uv})A+2\Delta t\sum_e\beta_o AT_a\end{aligned} \qquad (4)$$

The hidden difference equation of bound node:

$$\begin{aligned}&\left(\sum_e C_v\rho A\right)T_{i,t} + \frac{3}{4}\Delta t\sum_e\frac{K}{A}\left[(b_i^2+c_i^2)T_{i,t}+(b_ib_j+c_ic_j)T_{j,t}\right.\\&\left.+(b_ib_m+c_ic_m)T_{m,t}\right] + 2\Delta t\left(\sum_e\beta_o A\right)T_{i,t} + \frac{3}{2}\beta_o(L_1+L_2)\Delta t T_{i,t}\\&= \left(\sum_e C_v\rho A\right)T_{i,t-\Delta t}+\sum_e\gamma\bar{\sigma}\Delta\dot{\bar{\varepsilon}}_p A+\sum_e(-T_i\beta_{uv}\Delta\varepsilon_{uv})A+2\Delta t\sum_e\beta_o AT_a\\&+\frac{3}{2}\Delta t\beta_o(L_1+L_2)T_a\end{aligned} \qquad (5)$$

Where b_i, c_i, b_j, c_j, b_m, c_m represent the characteristic length; $T_{j,t}$, $T_{m,t}$ the temperature of the remaining two nodes of the element at time t; A is the element area, L_1, L_2 the two boundary lengths of bound element, $_o$ the heat dissipation coefficient and T_a the ambient temperature.

The node temperature at moment t can be solved from that at time $t - \Delta t$, and then the distribution and variation of temperature field can be decided from equations (4) and (5). Because the specimen used is thin enough, calculation is based on plane stress condition, and therefore solution of the hidden difference equation is stable (Norrie, 1978).

EXPERIMENTAL METHOD

In this study, an AGA Thermovision 780 scanning infrared camera was used to monitor the variation of temperature field of the specimen during process of deformation. It consists of a scanner mounted on a tripod, a recorder and a camera. A liquid nitrogen cooled InSb detector was used to monitor radiation in the range of 3 to 5.6μ of wavelength with a sensitivity of 0.1°C. One scan of the viewing field takes 1/25 second and results in an image composed of 280 lines containing 100 elements for each line. The detected infrared radiation is converted into an electrical signal and displayed on a cathode ray tube which may be recorded to a tape. It should be noted that this system has a high density of picture element and it requires no contact with the object of interest. Therefore, it is very satisfactory for use of measurement of temperature field of metal surface during tensile test.

(A) (B) (C)

Fig. 1. Three types of notches of the specimens.

Three types of notches of the specimens were used as shown in Fig. 1. The thickness of the specimen is 3.0mm which was machined from stainless steel palte. Type A is a circular central hole, B is a rhombic of 120° and C a circular notched with double saw-cuts. They have the same net loading cross section. In order to measure temperature accurately, a calibrated temperature radiation energy curve was used. The specimens were painted with a transparent coating to increase the emittance of the surface from the usual value of 0.2 to nearly 0.9, and thus the sensitivity of observation of the surface crack was enhanced (Huang, 1981). Tests were done on a tensile testing machine with a speed of 25mm/min. Loading-time curves with different types of notches are shown in Fig.2. Tests were carried out at room temperature. Thermograms were taken at desired intervals until fracture occurred. This allows one to locate not only the hottest spots on the specimen, but also the isotherm of interest within the temperature range covered by the thermograms.

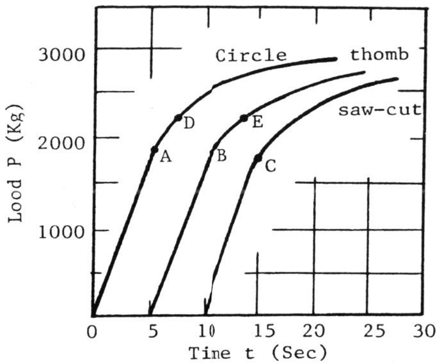


Fig.2. The loading-time curves with different types of notches.

RESULTS

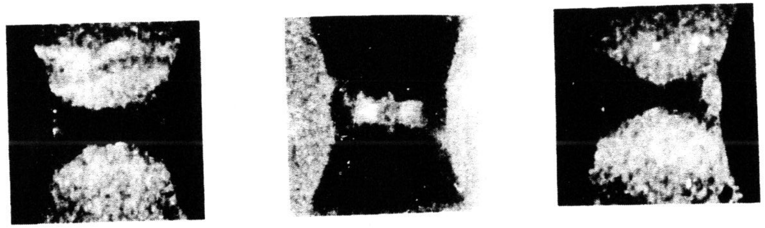
When the plastic zone was extended to the boundaries of the specimen during tensile deformation, the experimental and calculated results are shown as follows.

Fig.3 is the thermograms representing the distribution of temperatures of the specimens with different types of notches. Photo (A) and (C) are inverse images, that is, the darker the images, the higher is the temperature. Photo (B) is a normal image. Time recording of the thermograms is corresponding to A,B,C in Fig.2. Fig.4 shows the isotherm distribution and values indicated are variation of temperature (°C). Results of finite element analysis are shown in Fig.5. It can be seen the values of isotherm are decreasing with the severity of the notch at the same extent of deformation, that is, the heat generated is the highest with specimens of circular holes, and the least for that of circular hole with saw-cuts. Table I shows the radii of the roots of notches with measured temperature rise.

Ordinarily, the deformation of the notch root of the specimen with a small radius is more severe, and the rise of temperature should be higher, but this is not true, this can be explained: first, the area of deformation is so small that heat generated is swiftly conducted away; and secondly, part of heat is counterbalanced by the thermal-elastic effect as shown in Fig.6. This is the variation of temperature of the notch root of the double saw-cuts specimen during the process of elastic-plastic deformation. No temperature rise occurred before yielding set in, and there were small temperature drops as is predicted by equation (1).

TABLE I The Radii and Measured Temperature Rise of Different Notch Roots

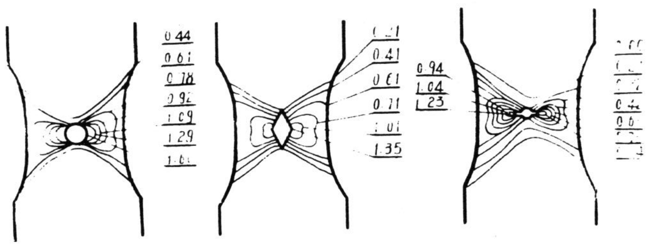
Hole form	Circular	Rhombic	Double saw-cuts
Radius(mm)	2.5	0.5	0.1
Rise of temp. (°C)	1.6	1.4	0.8



(A) (B) (C)

(A) and (C) inverted; (B) normal

Fig. 3. The thermograms when the plastic zone extended to the boundary.



(A) (B) (C)

Temperature T (°C)

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

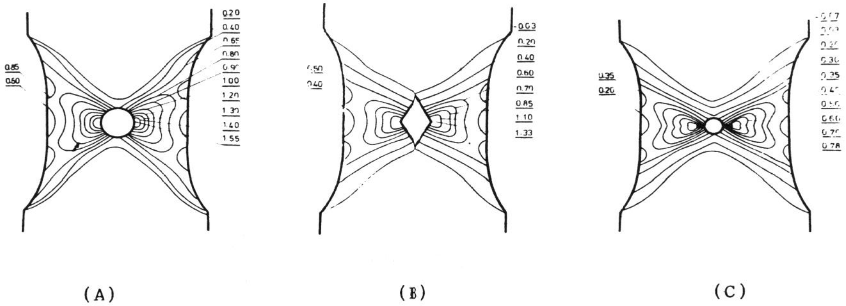


Fig. 5. The heat field results of finite element analysis when the plastic zone extended to the boundary.

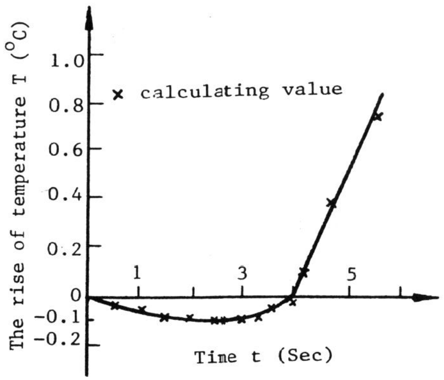


Fig. 6. The calculated result of the double saw-cuts specimen.

The dynamical process of the deformation heat field of the circular hole with double saw-cuts notched specimen.

Fig.7 shows the dynamical process of tensile deformation. Before the point C, the specimen was subjected to deformation within elastic range, and the thermograms should be negative, and this is true experimentally, as shown in Fig.6. The temperature at points 1, 2, 3 and 4 in Fig.7 were 0, -0.1, -0.15 and -0.2°C respectively. After point C on the curve, plastic deformation began to set in, zones of deformation were concentrated in the week sections of the notch roots, and so were the heat fields. Then the heat fields were gradually evenly distributed, and the butterfly images were gradually fade away. The temperature rise is higher and higher as the displacement is bigger and bigger. The maximum temperature rise at point of fracture is

26°C. It is of interest that there was a sudden infrared emission, this can be explained by the avalanche of dislocations at fracture . It should be pointed out that the maximum rise of temperature of the specimen was at the point where crack is propagating as checked by the metallographic observation of a polished specimen at point 7 in Fig. 7. The point of maximum temperature on the thermogram could be used to predict the starting point of fracture.

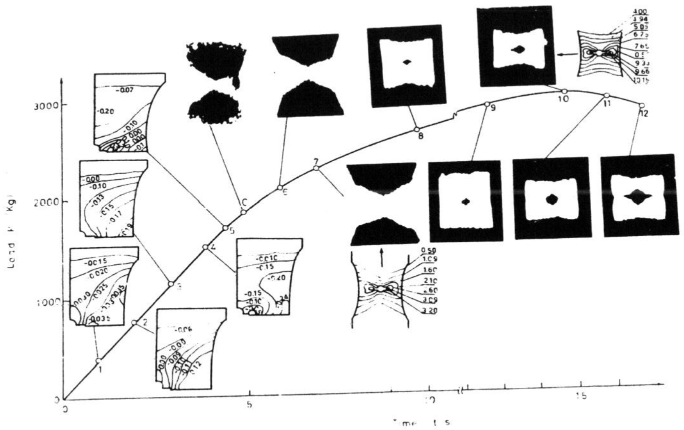


Fig. 7. The dynamical process of the deformation heat field with double saw-cuts specimen during the tensile test.

CONCLUSIONS

In this study, thermography and finite element analysis have been used to give the dynamical patterns of the heat fields of notch specimens during process of deformation.

During the tensile test, there is a small drop in temperature before yielding As plastic deformation proceeds, an obviously temperature rise is occured. When the specimen is near fracture, there is an abrupt infrared energy at the point of fracture. Therefore, the maximum temperature point of the specimen can be used to predict the most probable location of subsequent fracture damage.

A complete surface temperature field generated by local stress concentrations can be demonstrated by infrared technique and it has been proved as an useful method for studying the mechanical propety of materials as well as a tool of monitoring crack propagation and the temperature rise in the metals.