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QUANTITATIVE PLASTIC DEFORMATION ANALYSIS BY MEANS OF THERMOPLASTIC EFFECTS[1]

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ABSTRACT

This paper proposed a new method of quantitative plastic deformation analysis by means of thermoplastic effect. Then, the distribution of plastic strain rate for single shear specimen was obtained by using this method.

During the plastic deformation, obvious temperature increases occurred at the plastic zone due to the dissipation of plastic work. This phenomena was called thermoplastic effect. Based on general thermodynamics law, the plastic work rate was regarded as the internal dissipation heat source. In Fourier heat conduction law, the numerical solution of the heat source could be obtained by means of FDM (Finite Difference Method) while the distribution of temperature during continuum tiny time step was known. By using TVS (Thermal Video System), the distribution of temperature on the surface of specimen during the whole process of plastic deformation can be measured and processed. So the distribution of plastic work rate at any time during plastic deformation could be calculated by FDM. Also, the equivalent plastic strain rate could be resolved from the plastic work rate. The equivalent plastic strain could be obtained if the whole process of plastic deformation was analyzed. This new method we called Plastic Deformation Analysis by Thermal Emission (PDATE).

The plastic zone of a PVC single shear specimen was analyzed by PDATE. The device used in experiments was TVS–5500, made by Nippon Avionics Co., Ltd. The results of PDATE and FEM (Finite Element Method) was compared. On the basis of theories and experiment study, PDATE was proved to be realizable. At last, the new technique requirements on TVS for further study of PDATE was presented.

Keywords: Thermoplastic Effect, Plastic Work Rate, Finite Difference Method (FDM), PDATE, Thermal Video System (TVS), FEM, Heat Conduction, Thermodynamics

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1 INTRODUCTION

During plastic deformation, obvious temperature increases occurred at plastic zone due to dissipation of plastic work. The majority of plastic work (>90%) is converted to heat before cracking appears. In problems that involve both heat generation due to plastic work and heat conduction it is advantageous to define the converted plastic work fraction β as follows:

$$\beta = \frac{\dot{Q}}{\dot{W}^P} \tag{1}$$

where $\dot{Q}$ is the heat production density rate and $\dot{W}^P$ is the plastic work density rate. Generally, the converted plastic fraction is assumed to be a constant in the range 0.90–1.0, and can be obtained by some experiments. Using this definition in the Fourier heat conduction equation gives a partial differential equation for the temperature rise at plastic zone before cracking appears:

$$-k\nabla^2 T + \rho C_p \frac{\partial T}{\partial t} = \beta \dot{W}^P \tag{2}$$

where k is the thermal conductivity, ρ is the density, C_p is the heat capacity. By using the finite–difference method, the above partial differential equation at mesh node m, n and time i is approximated as: (for 2–D only)

$$\begin{aligned} \beta \dot{W}^P \big|_{m,n,i} = c\rho \frac{T^{i+1}_{m,n} - T^{i-1}_{m,n}}{2\Delta t} &- k\frac{T^i_{m+1,n} + T^i_{m-1,n} - 2T^i_{m,n}}{(\Delta x)^2} \\ &- k\frac{T^i_{m,n+1} + T^i_{m,n-1} - 2T^i_{m,n}}{(\Delta y)^2} \end{aligned} \tag{3}$$

where Δt is the tiny time increase; Δx, Δy is the distance between two nearest node.

By using Thermal Video System (TVS), the distribution of temperature on the surface of 2–D specimen T(x,y,t) can be measured and processed at every tiny time step during the whole process of plastic deformation, where Δt is the time resolution of TVS and Δx, Δy is the space resolution. So the distribution of plastic work density rate $W^P(x,y,t)$ can be obtained. According to plasticity, we know that:

$$\dot{W}^P = \underline{\sigma} : \underline{\dot{\varepsilon}}^P = \sigma_i \dot{\varepsilon}_i^P \tag{4}$$

where $\underline{\sigma}$ is stress tensor, $\underline{\dot{\varepsilon}}^P$ is strain–rate tensor, and σ_i is the stress intensity, $\dot{\varepsilon}_i^P$ is the equivalent plastic strain–rate.

To perfect plastic material, we know

$$\sigma_i = \sigma_s = \text{const.}$$

where σ_s is yield strength. So that the equivalent plastic strain rate can be expressed as follows:

$$\dot{\varepsilon}_i^P(x,y,t) = \frac{1}{\sigma_s}\dot{W}^P(x,y,t) \tag{5}$$

then

$$\varepsilon_i^P(x,y,t_N) = \frac{1}{\sigma_i}\sum_{j=1}^{N} W^P(x,y,t_j)\Delta t \tag{6}$$

To linearly hardening plastic materials,

$$\sigma_i = \sigma_0 + E'\varepsilon_i^P \tag{7}$$

where σ_0 is the initial yield strength. E′ is the tangent modulus. So we can get:

$$\dot{W}^P(x,y,t) = (\sigma_0 + E'\varepsilon_j^P)\dot{\varepsilon}_i^P = \sigma_0\dot{\varepsilon}_i^P + E'\varepsilon_i^P\dot{\varepsilon}_i^P \tag{8}$$

then

$$\int_0^t \dot{W}^P(x,y,t)dt = \int_0^t \sigma\dot{\varepsilon}_i^P dt + \int_0^t E'\varepsilon_i^P\dot{\varepsilon}_i^P dt \tag{9}$$

$$\sum_{j=1}^{N} W^P(x,y,t_j)\Delta t = \sigma_0\varepsilon_i^P + \frac{E'}{2}(\varepsilon_i^P)^2 \tag{10}$$

so

$$\varepsilon_i^P(x,y,t_N) = \frac{1}{E'}\left(-\sigma_0 + \sqrt{\sigma_0^2 + 2E'\cdot\sum_{j=1}^{N} W^P(x,y,t_j)\cdot\Delta t}\right) \tag{11}$$

To power law hardening materials,

$$\sigma_i = \alpha(\varepsilon_i^P)^n \tag{12}$$

where α is hardening coefficient, n is hardening exponent.

Generally, α and n are assumed to be constnat, So that

$$\dot{W}^P(x,y,t) = \alpha(\varepsilon_i^P)^n\dot{\varepsilon}_i^P \tag{13}$$

then

$$\sum_{j=1}^{N} \dot{W}^P(x,y,t_j)\Delta t = \frac{\alpha}{n+1}[\varepsilon_i^P(x,y,t_N)]^{n+1} \tag{14}$$

$$\varepsilon_i^P(x,y,t_N) = \left[\frac{n+1}{\alpha}\sum_{j=1}^{N} \dot{W}^P(x,y,t_j)\Delta t\right]^{\frac{1}{n+1}} \tag{15}$$

The method based on above theory we called Plastic Deformation Analysis by Thermal Emission (PDATE). By using this new method the distribution of plastic work rate fields on 2–D specimen can be obtained. Further more, the equivalent plastic strain can be carried out if the property of material is clear.

2 SPECIMEN AND EXPERIMENT

A serials PVC and 2024 aluminium single–shear sheet specimen under longitudinal tension was analyzed by PDATE. Figure 1 shows the shape of standard single–shear sheet specimen. The TVS used in experiments was AVIO TVS–5500, of which the maximum time resolution was 0.05 second and space resolution up to 0.5mm (standard lens). The temperature resolution can reach 0.05 ° K.

In experiment, the tension was under speed of 1.70mm / s and 4.67mm / s. Maximum temperature increases of aluminium was 4 ° K, while PVC specimen can reach 20 ° K due to the lower heat tansfore rate.

3 RESULT AND DISCUSSION

The Thermal–emission map of a PVC specimen during plastic deformation at four continue tiny time steps ($\Delta t = 0.1$sec) was analyzed. In Figure 2 the contour map of temperaturde fields on ciritical zone was presented. In Figure 3 the contour map of temperature increases between two time steps was presented. Figure 4 shows heat transfer rate at critical zone. In Figure 5 the contour map of equivalent plastic strain rate fields was presented, which was carried out by PDATE.

The result of PDATE is similar to FEM analysis.

4 CONCLUSION

Base on above discussion, we can conclude that the PDATE method is realizable, which introducing time factor and revise the error caused by heat transfer.

The method we presented here is worth further studing. In our study, plastic deformation analysis is limited to deformation before cracking appears.

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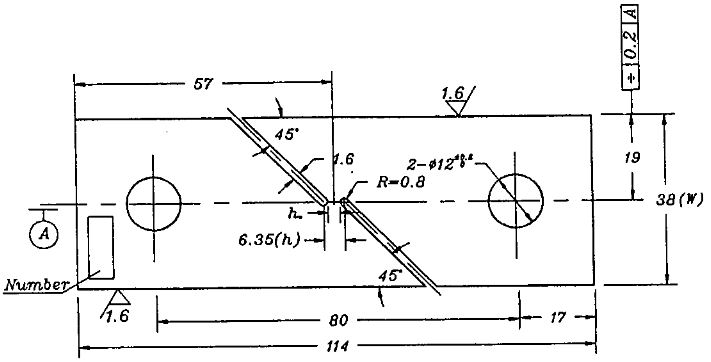

Fig.1 Standard single—shear sheet specimen

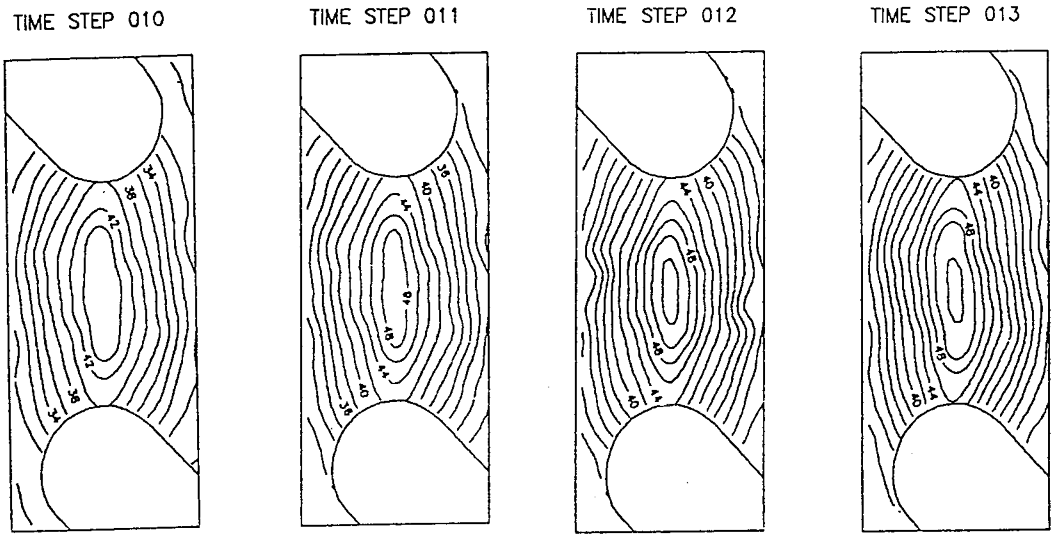

Fig.2 Contour map of temperature fields at four continue tiny time step

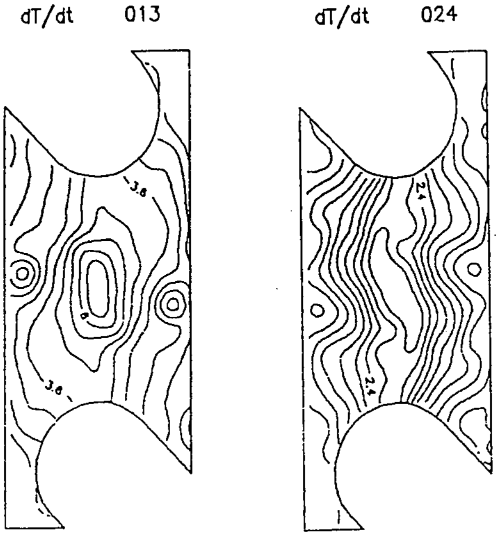

Fig.3 Contour map of temperature increases between two time step

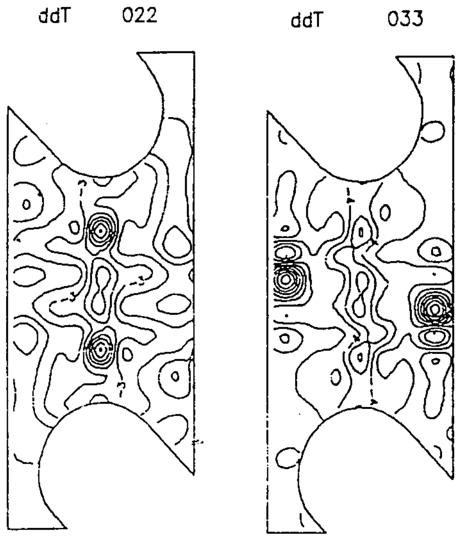

Fig.4 Heat transfer rate at plastic deformation zone

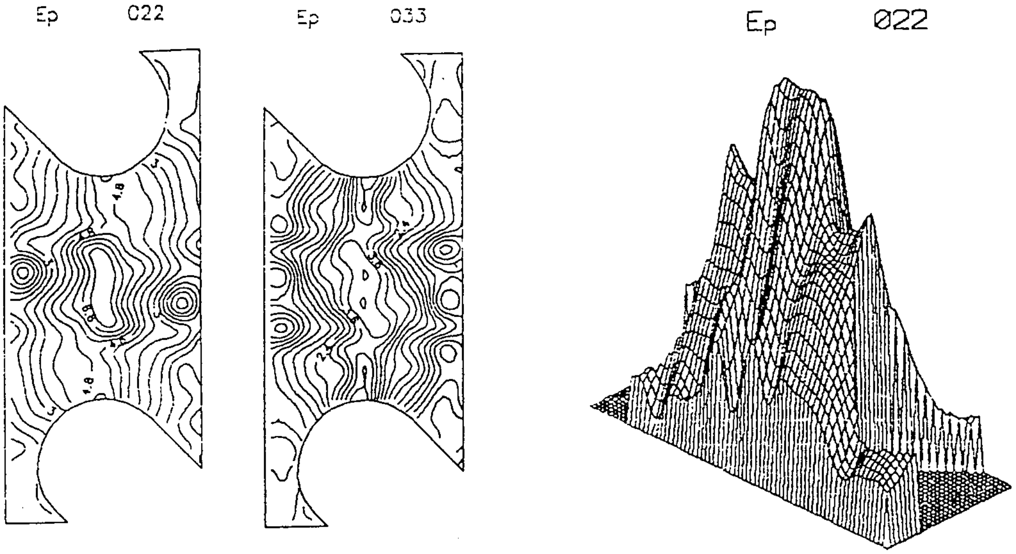

Fig.5 Contour map of equivalent plastic strain rate fields at two time step.