Crack Arrest in Metal Component with Double Spatial Cracks using Electromagnetic Heating

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Abstract. The temperature field around a crack tip is simulated for the case when crack arrest is proceeding in a test piece with prepared spatial cracks using pulse current discharge, the thermal-electrical coupling analysis method is applied numerically, and the results are verified experimentally. The numerical simulation and experiment results show that the deposit joint can be formed around the crack tip, and the radius of curvature around the crack tip increases remarkably instantly after pulse current discharged.

1. Introduction

The technique of crack prevention is strongly needed in current industrial production[1,2]. To prevent cracks in a mental component from propagation by the electromagnetic heating has become an effective way to extend its service life, and improve its security and reliability. However, the research on crack arrest by using electromagnetic heating is focused on the planar current conductor, because the limit on pulse current generator power, and just the spatial crack is not referred to. In this paper, the research on spatial crack arrest using electromagnetic heating is implemented. The technique is the key of the basic research which is applied in actual.

2. Numerical simulation

The numerical simulation method is proposed for analyzing the coupled field of thermal-electrical field. The electric capacitor discharge time is very short, and the coupled system is loose, so the method of the ordinal coupled is applied.

2.1. Equation of heat conduction Headers and footers
The temperature field of the test piece after pulse current discharged can be determined by solving the heat conduction equation with a heat source [3,4].

\[ \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + Q = \rho c \frac{\partial T}{\partial \tau} \]  \hspace{1cm} (1)

Where, \( \rho \) is the material density, \( c \) the thermal capacity, \( \tau \) the time, \( \lambda \) the thermal conductivity, \( T \) the local temperature and \( Q \) the internal heat source. The density \( \rho \), thermal capacity \( c \) and thermal conductivity \( \lambda \) are functions varying with the temperature \( T \). We are concerned about the influence of

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these parameters on the numerical simulation since the temperature gradient is very large. When the current is switched on, the entire specimen boundary is adiabatic. The temperature is uniform at the initial time and equal to the ambient temperature.

The internal Joule heat source can be calculated with the following expression:

\[ Q = I^2Rt = \frac{U^2}{R}t \]  

(2)

2.2. Equation of thermal-electrical coupled

The temperature field is analyzed by the method of thermal-electrical coupled. The coupled process is embodied by the interaction among the inner heat sources when the electric current flows, and changes (of thermal conductivity and specific heat) with temperature.

We have obtained the following finite element equation for the problem:

\[
\left[ \mu \right] V = I
\]  

(3)

Where, \(\left[ \mu \right]\) is the conductance matrix related to \(T\), \(I\) the node current vector, \(V\) the node voltage vector.

\[
\left[ C \right][\hat{T}] + \left[ K \right][T] = \{Q\} + \{Q^E\}
\]  

(4)

Where, \([C]\) the thermal capacity matrix, \([K]\) the thermal-transfer matrix, \([\hat{T}]\) deviation of temperature vector, \([T]\) the node temperature vector, \([Q]\) the thermal vector, \([Q^E]\) the internal heat source vector.

2.3. Finite element meshing

The metal component of Cr12 steel with double spatial cracks has been studied. It is shown in Figure1, and the finite element mesh of Model is shown in Figure2.

2.4. Results of numerical simulation

2.4.1 The temperature filed around crack tip

The temperature field contour band graphics is shown in figure3 when the discharge voltage is 5000V. The results given in figure 3 show that the current flows and concentrates due to the existence of the crack. In the small area around the crack tip, the effect of the current concentration is so remarkable that the temperature around the crack tip reaches more than 1600°C. This exceeds the melting points of the metal component. In the region far away from the crack tip, the effect of the current concentration is so weak that the temperature does not exceed the environmental temperature and does not affect the
properties of the metal. The contour bands of temperature in YZ cut plane is given in Figure 3. The contour bands of temperature in XZ cut plane is shown in Figure 4.

2.4.2 Analysis on current flowing over

The current vector flowing over in metal component at the moment of pulse current discharge is shown in Figure 5. Owing to the existing of spatial cracks in metal component, the current concentration is so remarkable that metal around the crack tip melts and a welded joint forms. The temperature at the crack tip is mainly affected by the flowing over, and the stronger the flowing over, the higher the temperature. If there is not crack, the current flowing over does not occur, and the temperature rise is un conspicuous, close to the temperature of environment. The current flowing over vector graphics uncovers the essence of crack arresting by using electromagnetic heating.

![Figure 2. The model of finite element mesh.](image1)

![Figure 3. Temperature contour bands in YZ plane.](image2)

![Figure 4. Temperature contour bands in XZ plane.](image3)

![Figure 5. Vector diagram of current flowing over.](image4)

3. Experimental investigate

The experiments were conducted on a super density pulse current generator (model ZL-2) which developed by authors. It’s shown in figure 6. The principle is as follows: the set of capacitors is charged up by the double voltage commutation circuit and the discharge of capacitance is controlled by a thyristor; as the metal component is connected in series into the capacitance discharge circuit, the current passing through the specimen can be changed by adjusting the capacity and discharge voltage.

The circular hole formed around the crack tips in tension test piece after the pulse current discharge which is shown in figure 7. Strong melting is found in a small spherical region near the
crack tips. Provided that the current intensity is high enough, the material melted is splashed, and the deposit joint forms around crack tips in the metal component. The experiments confirm the numerical simulation result.

**Figure 6.** Equipment of ZL-2. **Figure 7.** The appearance of fracture after crack arresting (×500)

### 4. Conclusion
Crack arrest through electromagnetic heating is an effective method for solving fracture problems in engineering practice. The data show that the temperature around crack tip rises instantly by Joule heat source processing when the current flows over. The crack tip will be melted and the small welded joint can form at a small sphere near the crack tip, which decreases the stress concentration. Thus, the goal of crack arrest can be reached. The results of numerical simulation correspond to the experimental analysis.

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