Abstract—This paper investigates the thermo-electric effects around the crack and notch tips under the electric current load. The research methods include the finite element analysis and thermal imaging experiment. The finite element solutions show that the electric current density field concentrates at the crack tip. Due to the Joule heating, this electric concentration causes the hot spot at the tip zone. From numerical and experimental results, this hot spot is identified. The temperature of the hot spot is affected by the electric load, operation time and geometry of the sample.

Keywords—Thermo-electric, Joule heating, crack tip, notch tip.

I. INTRODUCTION

Many researches have reported that the Joule heating effect can induce the local hot spot or melting area at the crack tip [1]-[8]. This phenomenon is a kind of the thermo-electric effect. As shown in Fig. 1, when the crack tip is subjected to the electric load, the electric current density field concentrates at the crack tip. Due to the Joule heating, the electric concentration causes the hot spot at the crack tip zone.

In the past studies [1]-[8], the results demonstrated that the crack tip can melt when large electric energy is applied. After the cooling process, the melting area can become a hole at the crack tip. This hole, like a drilled hole, can reduce the stress concentration and remove the stress singularity at the crack tip.

II. PROBLEM DEFINITION

In Fig. 2, it shows the sample geometry and electric load of this research. The thin plate has the dimensions $W \times L$ and thickness $e$. The crack or notch length is denoted as $a$. The notch angle is $\alpha$. The sample is subjected to a direct current (DC) $i_0$. The material type of the sample is the SUS 304 stainless steel. Table I lists the material data of the SUS 304 stainless steel [9]. The thermal conductivity and electric resistivity are temperature-dependent.

The following conditions are considered in this study:

1. Three-dimensional analysis
2. Thermo-electric coupled-field
3. Transient heat transfer
4. Convection on air/sample interface
5. Steady electric current (DC current)
6. Temperature-dependent material data
(7) Electric insulation on crack surface

Due to the Joule heating effect, the sample is heated. The thermal image camera (designed by FLIR Co.) is used to capture the surface temperature field of the sample. The sample is a steel strip as shown in Fig. 5. It has an edge crack in the central region. To capture the surface temperature image, the sample must be coated by the black paint.

![Fig. 3 Finite element model](image)

![Fig. 4 Experimental facilities](image)

![Fig. 5 Sample](image)
VI. RESULTS AND DISCUSSIONS

A. Finite Element Results

The finite element model as shown in Fig. 3 uses the coupled-field analysis. The initial and ambient temperature are 26°C. The natural convection coefficients applied on the strip surfaces are calculated from the simplified formula in Ref. [13]. As a result, Figs. 6 and 7 show the electric current density and temperature field under $i_0 = 5$ A at 60 s. It can be seen that the Joule heating effect causes a high temperature area (hot spot) around the crack tip. Also, there is a local concentration of the electric current density near the crack tip. Similar to the elastic stress field, the electric current density also has the $r^{-1/2}$ singularity at the crack tip [2].

![Fig. 6 Electric current density vectors (A/m²)](image)

![Fig. 7 Temperature contour (°C)](image)

**B. Comparison of Two Methods**

In this experimental study, the sample geometry and all conditions are the same as the finite element model in Section VI A. Fig. 8 shows the thermal image of the steel strip with a crack. There is a local hot spot around the crack tip.

The crack tip temperatures with time increments are shown in Fig. 9. The finite element results (numerical results) are close to experimental results. It demonstrates the good prediction of the numerical simulation.

![Fig. 8 Thermal image (°C) ($i_0 = 5$ A at 60 s)](image)

![Fig. 9 Time-history results](image)

**C. Effects of Geometry and Electric Load**

In the experiments of this section, effects of the sample geometry and electric load are discussed. In Fig. 10, the time-history data of the crack tip temperature are shown with different sample thickness. Due to the current density, the thinner case has higher temperature.

![Fig. 10 Time-history results](image)
The concept and result of this research can be applied to the crack detection. Using the thermal camera and image, the crack tip location can be determined. On the other hand, this research can be applied to the crack arrest. Under the high electric energy, the crack tip can melt and shrink to a hole. The crack tip hole can arrest or stop the further crack propagation.

ACKNOWLEDGMENTS

The authors would like to thank the Ministry of Science and Technology in Taiwan for the financial support under contract numbers NSC 101-2221-E-131-011 and MOST 103-2221-E-131-015. Also, the authors appreciate the support of the research project 103-AcademicResearch- E-02 of Ming Chi University of Technology.

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