Eddy current thermography and its application to inspecting impact fatigue defect in steel parts

Suixian Yang¹, Luye Liu¹ and Jingyuan Yang²
1 School of Manufacturing Science and Engineering, Sichuan University, Chengdu, 610065, China, yangsx@163.com
2 School of Mechatronics Engineering, Southwest Petroleum University Chengdu, 610500, China, 305701051@qq.com

Abstract

In this paper, the possibility of applying eddy current thermography to detecting impact fatigue damage in steel component has been investigated. The principle of the change of material microstructure and stress distribution in the material due to impact fatigue damage has been analysed. It has been discovered that the change of material microstructure and stress distribution in steel part due to impact fatigue damage will lead to changes of heat conduction and resistivity of material. This kind of material property change will lead to non-uniform distribution of induced eddy current flow around the damaged area if high frequency alternating current applied to an impact fatigue damaged component. An inspection system is established to illustrate the proposed method. Image processing are presented in detail to locate and quantitative evaluate damages in the sample.

Keywords: Eddy current, Impact, Infrared, Steel

1. Introduction

Impact fatigue will lead to residual stress accumulation in material. To inspect impact fatigue damage can be undertake by identifying the extent of residual stress in a component. Residual stresses caused by inhomogeneous deformations in component will influence on its performance characteristics in equipment, such as deformation, static and dynamic strength, or the strength of the contact. Hole-drilling strain gauge technique is an usual standard method to determine residual stresses in material [1]. There have amount of demands on evaluating residual stress with a non-destructive testing approach. To obtain the distribution and extent of residual stress in material, the non-destructive methods used include X-ray diffraction and ultrasonic and magnetic techniques [2, 3]. C. Xu introduced an ultrasonic stress testing and calibration system [4]. The interactive relationship between high energy ultrasonic and residual stress field was investigated for in situ regulation of residual stress. Magnetic approaches determine residual stress by using the impact of stress on permeability, hysteresis, and magnetic Barkhausen noise. R. Stegemann et al. [5] researched on the evaluation of residual stress with high spatial resolution GMR (giant magneto resistance) sensors. The residual stress of steel TIG welds was characterized by neutron diffraction and by residual magnetic stray field mappings. M. Rabung, et al. [6] investigated non-destructive evaluation of the micro residual stresses of IIIrd order by using micro magnetic methods. M. Roskosz and M. Bieniek [7] presented a residual stress evaluation method using the gradients of the residual magnetic field (RMF) components. A quantitative method has been
presented by A. Sorsa, et al. [8] to predict residual stress and hardness in case-hardened steel based on the Barkhausen noise measurement. Researchers proposed new methods to determine residual stress, for example, electronic speckle pattern interferometry [9]. J.-N. Aoh and B.-L. Lyu [10] presented a full field residual stress determination method by using hole-drilling and electronic speckle pattern interferometry (ESPI) with phase unwrapping. Positioning optimised eddy-current sensors close to a pre-stressing cable, force and strain in steel reinforced concrete were measured by collecting the coil impedance of an eddy-current sensor and concluding the change of stress in steel of reinforced concrete elements in reference [11]. The near-surface residual stress in surface-treated metals was identified by iterative inversion method for eddy current [12].

In this paper, eddy current thermography is employed to identify impact residual stress in steel component. It has been validated that the possibility of detecting impact fatigue damage in steel component by using eddy current thermography.

2. Impact residual stress influences on material characteristic

Due to the magnetoelastic effect, mechanical stress has an influence on the energy anisotropy of magnetic domains, which most often results in changes in permeability [7]. Impact residual stress results in changes in material conductivity. The distance between atoms and the distortion of the lattice inside the material will increase or decrease due to stress in material and lead to the changes in material resistivity. The resistivity variation follows:

$$\rho = \rho_0 (1 + k\sigma)$$  \hspace{1cm} (1)

Where $\rho_0$ is the resistivity with no load, $k$ is the stress factor, and $\sigma$ is the stress.

The thermal conductivity of material is also affected by impact residual stress existing in the material. Heat transfer of solid materials is mainly achieved by lattice vibrations (phonons), and that of metal materials are delivered by free electrons. Due to the interaction forces between the particles, the weaker vibrations of the particles vibrate under the influence of the stronger vibrational masses, which results in thermal motion. The stress makes the internal force of the material unstable, affects the vibration of the lattice and the movement of free electrons, and thus affects the thermal conductivity of the material. The thermal conductivity $\lambda$ equation is as follows:

$$\lambda = \frac{1}{3} \frac{c}{\bar{v}} l$$  \hspace{1cm} (2)

Where $c$ is the specific heat of phonon, $\bar{v}$ is the speed of phonons, and $l$ is the average free path of phonons (the distance travelled by phonons in two collisions).

3. Probability of residual stress detection with eddy current thermography

Eddy current thermography has been applied to inspect defects in conductive materials by researchers [13-17]. If high-frequency alternating current is applied closely to the conductive materials, induction eddy current will generate on its surface or near-surface and the detected area will be heated due to Joule’s heating. If a defect exists in
conductive material, the eddy current distribution and the process of thermal diffusion will be disturbed. That is to say, when the eddy current encounters a discontinuity, such as crack or non-uniform material structure, it will be forced to divert, leading to an increase of the eddy current density in the crack vicinity or the defect region.

According to equations (1) and (2), resistivity and thermal conductivity of material will change if residual stress exists in material, leading to non-uniform heat distribution inside the material and non-uniform surface temperature distribution due to Joule’s heat induced by excitation coil and its propagation inside the material. The temperature field can be recorded by using an infrared camera. By analysing the infrared images, the distribution and level of residual stress in the material can be identified.

4. Experiment and results

4.1 Experiment system and testing parameters

The experiment system consists of an induction heater (Easyheat224), an IR camera (FLIR SC7500), and a computer. Figure.1 shows the system set-up.

![Figure.1 set-up of the experiment system](image)

Four samples, aircraft brake pad, are used in the experiment, which include one new part (labelled m3605) and other three with different impact damages (labelled m2380, m7438, and m7591). The samples have dimension with 220mm*30mm*22mm. The material of the sample is tungsten alloy.

The excitation current is 480A, the excitation frequency is 225 kHz. The heating time is 200ms and the IR image is recorded in 6 seconds including the heating and cooling periods. The frame rate is set as 100 fps.

4.2 Results and discussions
The thermal images obtained at the end of heating period are listed in the first row in Table 1. The second row of Table 1 shows the line scan temperature distribution contrast of damaged sample with the new one alone with the red line in the first row.

<table>
<thead>
<tr>
<th>Table 1. Thermal images of the damaged samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal image</td>
</tr>
<tr>
<td>m2380</td>
</tr>
<tr>
<td><img src="image1" alt="Thermal image of m2380" /></td>
</tr>
<tr>
<td>m7438</td>
</tr>
<tr>
<td><img src="image2" alt="Thermal image of m7438" /></td>
</tr>
<tr>
<td>m7591</td>
</tr>
<tr>
<td><img src="image3" alt="Thermal image of m7591" /></td>
</tr>
<tr>
<td>Contrast of temperature distribution</td>
</tr>
<tr>
<td><img src="image4" alt="Contrast of temperature distribution" /></td>
</tr>
</tbody>
</table>

It can be seen obviously in Table 1 that the hot regions in the images could be the impact damaged area. In those areas, the temperature digital level is significantly greater than that of the new one. Therefore, the impact damage region can be easily identified from the IR images and the line scan features of the temperature distributions.

![Figure 2 (a) Thermal image of m2380; (b) Temperature history curve](image5)

A comparison analysis has been conducted to understand the extent of impact residual stress in the samples. The curves of temperature history including heating and cooling periods of points labelled A, B, C in damaged sample (m2380) as shown in Figure 2(a) have been obtained by processing the images with Matlab. And that kind of curve of the new sample is also obtained. Those curves are presented in figure 2(b). It can be found from Figure 2(b) that the temperature rise of the damaged sample is obviously larger than that of the new one. There is bigger temperature change in the damaged area. The conclusion could be reached according to the curves of temperature history that the extent of damage is A>B>C. It can also be seen from the curves that the greater the
damage is, the higher the temperature level. The curve slope of rising part of the temperature history is also larger.

5. Conclusions

The results obtained from the experiments prove that it is possible to identify impact fatigue damage or impact residual stress in steel component by using eddy current thermography. The impact damage regions can be recognized from the IR images directly. The extent of damage can be evaluated by processing the IR images to analysing the temperature history of the interest points.

Acknowledgements

The authors would like to thank China National Science Foundation (NSFC 51275325) for financial support to this work.

References