Research on temperature-magnetic properties based on metal magnetic memory testing technology

Zhenfa Bi¹,a*, Tao Wu¹,b, Pengli Fang¹,c, Zongkai Wang¹,d
¹School of Railway Transportation, Shanghai Institute of Technology, Shanghai, China
Email: bizhenfa@sit.edu.cn
bEmail: 1535501303@qq.com, cEmail: 472858272@qq.com,
dEmail: 1064169568@qq.com

Abstract: during the running of high-speed railway, the vibration and friction between wheel set and track will cause the temperature rise between wheel set and track. The metal magnetic memory detection technology is used to detect the small fault of wheel set, and the temperature will have a certain impact on the magnetic memory signal. In order to study the quantitative relationship between temperature and magnetic memory signal, the temperature magnetic property of 25CrMo4 material is proposed in this paper. Through the temperature magnetic experiment and simulation analysis of the material specimen, it is concluded that when the temperature is lower than Curie point, the magnetic flux leakage of the sheet is basically stable. The value in tangential direction is 130 A/m, and the value in normal direction is 0 A/m. When the temperature reaches Curie point, the value of the tangential direction changes to 169.9 A/m, and the normal direction is still 0 A/m; And the temperature magnetic numerical simulation curve is constructed, which provides the basis for carrying out magnetic signal to material small fault under coupling load, and provides the basis for non-destructive testing.

1. Introduction:
As a new nondestructive testing method, metal magnetic memory testing (MMMT) has been widely concerned by scholars at home and abroad since it was proposed[1-4]. Because the temperature of the specimen is not necessarily normal temperature in the actual test, the influence of different temperatures on the magnetic memory testing technology must be considered. In the previous literature, the influence factors of magnetic memory detection are studied at room temperature, but the influence of temperature change on magnetic memory signal is not considered. Wen Qingsong[5] established a typical sample simulation model, applied different temperatures and applied loads for ANSYS finite element simulation, to study the influence of temperature change on magnetic memory testing. Yin Aijun[6] analyzes the influence of temperature on magnetic flux leakage signal when there is an external magnetic field in magnetic flux leakage detection, and studies the characteristics of magnetic flux leakage signal. In this paper, the metal magnetic memory detector is used to detect the leakage magnetic field of the plate which is only affected by the geomagnetic field. The variation of the leakage magnetic field of 25CrMo4 material with temperature is studied under the condition of no external load on the plate.

2. Theoretical basis
25CrMo4 alloy structural steel is a ferromagnetic material. The change of temperature will cause the
change of permeability of ferromagnetic material. When the ferromagnetic material is saturated or nearly saturated, the magnetic flux leakage field induction will also change accordingly. In order to realize thermal magnetic coupling simulation, it is necessary to establish the relationship between temperature field and magnetic field. The nonlinear relationship between relative permeability and temperature T of ordinary carbon steel is shown in equation (1) and equation (2):

\[
\mu_r = 1 + \frac{J_{ro}}{1 - \sqrt{(H_s + 1)^2 - 4H_s(1-a)}} \cdot \text{COEF}(T) \tag{1}
\]

\[
H_s = \mu_0H \frac{\mu_0 \text{COEF}(T) - \mu}{J_{ro}} \tag{2}
\]

\[
\text{COEF}(T) = \begin{cases} 
1 - \exp \left( \frac{T - T_1}{c_0} \right), & T < T_1 \\
1 - \exp \left( 10 \left( \frac{T_2 - T}{c_0} \right) \right), & T > T_2 
\end{cases} \tag{3}
\]

Where, \( \mu_0 \) is the vacuum permeability, and the size is \( 4\pi \times 10^{-7} \), \( \mu_{r0} \) is the relative permeability at \( t = 0 ^\circ C \), \( T_c \) points the temperature for Curie, and \( a=0.4 \) is the knee point adjustment coefficient, that is, the position and shape parameter of the inflection point in the curve. When the applied magnetic field intensity \( H \) is constant, the corresponding relationship between the relative permeability and temperature of ferromagnetic materials can be established, which is the theoretical basis for the subsequent thermal-magnetic analysis.

### 3. Experimental study

25CrMo4 alloy structural steel is selected as the research object. 25CrMo4 is the wheel set material of CRH3 "harmony" high-speed EMU. It has very good mechanical properties, high ductility, weld ability and good harden ability. The main alloy composition is shown in Table 1.

| Element name | C | Si (Max) | Mn | P (Max) | S (Max) | Cr | Mo |
|--------------|---|---------|----|---------|---------|----|----|
| proportion (%) | 0.22-0.29 | 0.4 | 0.6-0.9 | 0.025 | 0.035 | 0.9-1.2 | 0.15-0.3 |

Xmt-8000 high temperature resistance furnace is used to heat the plate. The maximum heating temperature of the intelligent temperature control furnace is 1200 \(^\circ\)C, which can accurately control the furnace chamber to reach the preset temperature. Tsc-2m-8 stress concentration magnetic detector is used to measure the leakage magnetic field signal on the surface of the specimen. The detector is developed by Russian "dynamic diagnosis" company, which can evaluate the stress and deformation of equipment according to metal magnetic memory detection technology. The high temperature resistance furnace and metal magnetic memory detector are shown in Fig. 1 and Fig. 2 respectively.
In this experiment, three 25CrMo4 plates with the same size are selected, the specific dimensions of the plate are shown in the figure 3, that is, the length is 200 mm, the width is 50 mm, and the height is 1.5 mm. In order to ensure the accuracy of the experimental data and eliminate the random error in the measurement, three sheets with the same shape and size were selected to measure them respectively. In each experimental measurement process, the consistency of the plate position and the signal collection height, that is, the lift off value should be strictly maintained to reduce the influence of the position on the experimental results. The normal magnetic memory signal extraction path is vertical to the plate, and the tangential magnetic signal extraction path is along the detection line. The magnetic memory detector has 8 channels, that is, the tangential and normal magnetic memory signals of 4 detection lines are extracted.

Put the plate into the high temperature resistance furnace and heat it to the specified temperature. In order to ensure that the temperature inside and outside the material is consistent, the material needs to be kept for a period of time; Place the plate in the designated position, and use the magnetic memory signal acquisition car to move slowly from one side of the plate to the other side close to the plate. We would remove the trolley, store the magnetic memory signal value and put the plate back to the heating furnace. Then we reset the heating and insulation temperature, and repeat the above cycle until the measurement is completed. Repeat the above operations for the other two plates in turn, and finally collect and sort out all the data.

4. Data analysis
The magnetic field intensity values in the tangential and normal components of the magnetic field of the three plates at 400 °C are shown in Figure 4:
Fig. 4 Magnetic field intensity at different positions

The plate is in the state of free expansion. In the tangential direction, the magnetic flux leakage strength is basically unchanged, that is, it is maintained in the range of $-118 \, \text{A/m} - 136 \, \text{A/m}$. In the normal direction, the magnetic flux leakage strength at each point is maintained near $0 \, \text{A/m}$, that is, in the range of $-5 \, \text{A/m} - 5 \, \text{A/m}$, the magnetic flux leakage strength at each position of the plate is nearly the same. The signal modulus values of three plates at different temperatures are calculated. The curve of magnetic signal modulus value changing with temperature can be obtained as shown in Fig. 5. The random error can be eliminated by averaging the signal modulus values of three sheets, and the distribution diagram of temperature magnetic field intensity average value of sheets can be obtained, as shown in Fig. 5 below.

As shown in Fig. 5: at 100-300 °C, the magnetic flux leakage of the plate is 130 A/m. as the temperature continues to increase, the internal material properties of the plate change at 300-700 °C, the magnetic domain structure changes due to the increase of internal molecular kinetic energy, and the magnetic flux leakage decreases slightly to 110 A/m. When the Curie point (700-800 °C) is reached, the permeability will drop sharply, resulting in a sharp increase in the leakage magnetic field, up to 169.9A/m.

The temperature magnetic field intensity curve shown in Fig. 5 is divided into two sections for fitting. The temperature magnetic field intensity fitting diagram in the two temperature ranges of 100 °C - 700 °C and 700 °C - 900 °C is shown in Fig. 6. When the temperature is 100 °C - 700 °C, it is approximate to the parabola with the opening downward, and the quadratic polynomial is used for fitting. At 700 °C - 900 °C, it is similar to the parabola with the opening upward, and the quadratic polynomial fitting is also used. The fitting results are shown in equation (4):

\[
\text{Equation (4)}
\]
Fig. 6 Fitting curve of magnetic field intensity

\[
H_{sum} = \begin{cases} 
-3.2 \times 10^{-2} T^2 - 0.0123T + 133.44 & 100 < T < 700 \\
0.0026T^2 - 3.98T + 1629.7 & 700 < T < 900 
\end{cases}
\] (4)

5. Conclusion:

(1) Through the experimental study, the magnetic flux leakage strength of 25CrMo4 material at different temperatures is measured, and the change rule of magnetic memory signal of 25CrMo4 material at different temperatures is obtained. The relationship between the magnetic field strength and the temperature rise in the free expansion state is summarized. The tangential magnetic field strength is stable at 130A/m before reaching the Curie temperature. When the temperature exceeds the Curie point, the permeability decreases sharply and the tangential magnetic flux leakage increases rapidly to 169.9A/m. In the normal direction, the magnetic field intensity is about 0A/m at each temperature.

(2) By fitting the experimental data, the piecewise quadratic polynomial fitting formula of the magnetic field intensity changing with temperature within 900 ℃ is obtained. It provides the basis for the influence of magnetic signal on material failure under coupling load and for nondestructive testing.

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