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Experiment Research on the Attenuation Law of KMN Metal Magnetic Memory Signal

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In order to clear the timeliness of metal magnetic memory signal strength on the specimen surface after unloading, an artificial defect is prefabricated on the specimen surface of KMN, which is commonly used in the centrifugal compressor. Then conduct a static tension experiment on the specimen, and measure the normal magnetic field strength of artificial defect surface of the unloaded specimen periodically with EMS-2003, which is an intelligent magnetic memory tester. Furthermore, the time domain model of the magnetic memory signal is built and the attenuation law of magnetic field intensity with time is revealed. The results show that: the surface magnetic field signal value reduced with time after unloading. In other words, that is timeliness of the magnetic field signal.

1. Introduction

Metal magnetic memory testing technique is a kind of fast nondestructive testing method used to detect stress concentration areas of specimens based on metal magnetic memory effect, it can diagnose the internal stress concentrated areas of ferromagnetic metal specimens, such as microdefect, initial failure and damage, prevent sudden fatigue damage. (Doubov (1997) reported). At present, the researches of metal magnetic memory are mainly focused on the engineering application, while the microscopic mechanism of metal magnetic memory is always an academic research hotspot, a relatively complete and rigorous theoretical system has not formed until recently. This confines the development of magnetic memory testing technology, the corresponding relationship between the damage degree of stress concentration region of the measured specimen and the magnetic memory signal cannot be characterized quantitatively. While magnetic memory signal value whether changes and has timeliness after unloading have not been resolved.

At present, the decision rule of stress concentrative area in widely used is proposed by Russian expert professor Doubov, the region that the tangential component of leakage magnetic field Hp(x) has a maximum value and the normal component Hp(y) changes sign and has a zero point is the stress concentrative area. Therefore by means of measuring the normal component of leakage magnetic field Hp(y) and then calculate the gradient value K=dHp(y)/dx, the stress concentration area can be concluded (Doubov (1999) reported). This criterion can determine qualitatively the damage areas of workpieces, but cannot predict and evaluate the life of workpieces quantitatively. However, this criterion begins to be questioned in recent years. LIANG Zhifang etc. study and find that no zero point position also exists a stress concentration and zero crossing point position is not consistent with stress concentration in some cases. And he draw a conclusion that the stress concentration and Hp (y) zero crossing point exist complex relationships, not all the stress concentration position have zero crossing point of metal magnetic memory testing signals, Only by take the zero crossing point of Hp (y) signal as characteristics to judge the stress concentration position is prone to miscarriage(which was confirmed by LIANG et al (2006)).In view of this, JIAN Xingliang puts forward a discriminant method of stress concentration area based on magnetic field gradient, studies the relationship between magnetic field gradient and stress when online and offline measuring and conclude that surface magnetic field gradient of workpieces can reflect the maximum stress of workpieces suffered. In addition, the study also found that the magnetic memory signal reduce over time after unloading and propose the

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timeliness of using metal magnetic memory technology to detect stress concentration(JIAN et al(2010) reported).
This paper base on a specimen made of KMN material, which is commonly used in centrifugal compressors, prefabricated an artificial defect on it and then conducts a static tension experiment. Measure the normal magnetic field strength of artificial defect surface of the specimen periodically with EMS-2003, which is an intelligent magnetic memory tester, a magnetic memory signal time domain model is built and the attenuation law of magnetic field intensity over time is revealed.

2. Experimental process

2.1 Specimen preparation

The material KMN is chosen in this study, which is commonly used for a centrifugal compressor. An artificial defect in the middle of the specimen about 0.18 mm wide and 0.5 mm deep is processed by using the wire-cutting technology as show in Fig. 1. Any stress relief treatment after stretching is not allowed. In this way, an artificial stress concentration area can be created in the center of the specimen for the following measurement.

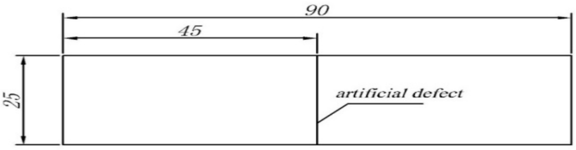

Figure 1: Tensile specimen schematic diagram

2.2 Experimental equipment and method

Tensile experiments are conducted in a universal material tensile experimental machine of OM-8750B and the normal magnetic field intensity in the center of an artificial defect is detected by an intelligent magnetic memory/eddy current detector of EMS-2003 (Doubov (2013) reported).
The environment temperature of this experiment is from 20 to 25 degrees Celsius. Tensile experiment is in the rate of 1 mm/min to 40000 KN and keeps the stress state for 1 minute, then conduct an off-line measuring. A specimen is placed in the center of an experimental table; testing sensor probe is perpendicular to the artificial defect center of the specimen. Electromagnetic interference is precluded to the scope of 5m around the experimental table (K. Yao et al (2012) and Penglin Zhang et al (2013) reported). When the lift-off height from the testing sensor probe to the specimen is 4mm, the detection effect is best, which is verified by experimental test, so the lift-off height is fixed at 4mm (LI Yuanli et al (2012) and Yu Feng-yun et al (2006) reported). The experimental period is 6 months. The position of the specimen and the sensor probe should not change during the entire experimental period. Measuring the normal magnetic field strength of the artificial defect center regularly, they are used in subsequent analysis. The experimental system is shown in Fig. 2.

Figure 2: Experiment system

3. Results and discussion

3.1 Experimental results and processing

It is found that the single measured data of the workpiece changed relatively in a day, due to the globe magnetic variation. The equipment needs to preheat five to ten minutes in order to eliminate the impact of the equipment heating. To ensure the repeatability and accuracy of the experiment, open the equipment at a fixed time every day and preheat it for twenty minutes, and then take one thousand data as a set of data, calculate the average value as the sampling value of this set. Then take a set of data every five minutes, totally take seven sets of data that are half an hour data. Take the average of these seven sets data as the normal magnetic field intensity that day. 6 months data is summary as show in Tab.1 and a data change trend curve is drawn as show in Fig.3.

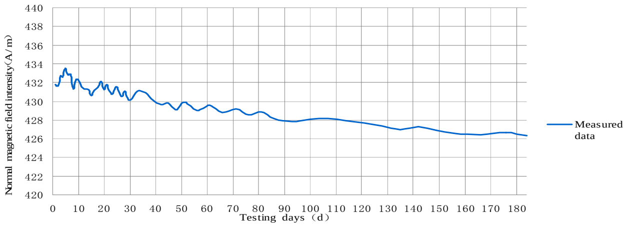

Figure 3 Normal magnetic field intensity testing data diagram

Table 1: Normal magnetic field intensity testing data

Day(d)	1	2	3	4	5	6
Magnetic Value($A{\cdot}m^{-1}$)	431.772	431.645	432.76	432.589	433.554	432.811
Day(d)	7	8	9	10	11	12
Magnetic Value($A{\cdot}m^{-1}$)	432.885	431.281	432.299	432.199	431.816	431.366
Day(d)	13	14	15	16	17	18
Magnetic Value($A{\cdot}m^{-1}$)	431.317	431.259	430.565	431.118	431.415	431.596
Day(d)	19	20	21	22	23	24
Magnetic Value($A{\cdot}m^{-1}$)	432.096	431.192	431.75	431.063	430.723	431.112
Day(d)	25	26	27	28	29	30
Magnetic Value($A{\cdot}m^{-1}$)	431.562	430.94	430.496	431.085	430.341	430.124
Day(d)	33	36	39	42	45	48
Magnetic Value($A{\cdot}m^{-1}$)	431.094	430.881	430.101	429.65	429.788	429.057
Day(d)	51	56	61	66	71	76
Magnetic Value($A{\cdot}m^{-1}$)	429.898	429.014	429.533	428.783	429.202	428.565
Day(d)	81	86	93	100	107	114
Magnetic Value($A{\cdot}m^{-1}$)	428.883	428.133	427.798	428.025	428.141	427.898
Day(d)	121	128	135	142	149	156
Magnetic Value($A{\cdot}m^{-1}$)	427.665	427.376	426.969	427.272	426.892	426.528
Day(d)	166	176	184			
Magnetic Value($A{\cdot}m^{-1}$)	426.433	426.621	426.323			

Use measured data to do the n-order polynomial fitting. The one which has the smallest polynomial fitting error is the optimal solution; take it as the optimum fitting equation of the measured data. Normal magnetic field intensity y is obtained when generation x, the number of experimental days, into the equation. Further, square the difference between calculated value and measured value of the magnetic field intensity, then fitting difference of one point is obtained, add fitting differences of every point to get approximation between fitting curve and measured curve, take the most close to the measured curve equation as the optimal solution.
By polynomial fitting function in MATLAB polyfit (x, y, n), the linear, quadratic and cubic polynomial fitting results are as follow:

$$y_1 = - 0.03571\, x + 431.95 \quad (1)$$

$$y_2 = 0.00017\, x^2 - 0.06245\, x + 432.48 \quad (2)$$

$$y_3 = - 9.34780\times10^{-7}\, x^3 + 0.00041\, x^2 - 0.07800\, x + 432.66 \quad (3)$$

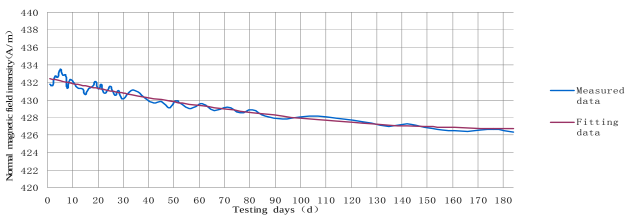

Figure 4: Measured and fitting data comparison chart

The result of the cubic polynomial fitting shows that cubic term coefficient is very small, higher fitting is not needed.
The equation of fitting error of the fitted curve:

$$A_n = \sum_{i=1}^{57} (y_{calculated\ i} - y_{measuredi})^2 \quad (4)$$

The sums of polynomial fitting error for linear, quadratic and cubic are: 20.32、11.95、11.31.Considering the cubic term coefficient is very small, it is not used. Depending on the principle of minimum fitting error, choose the quadratic polynomial fitting as the final regression equation. The comparison between the measured data and the fitting data is shown in the Fig.4.

3.2 Analysis and discussion

The attenuation of metal magnetic memory signal on the surface of the metal specimens can be explained by energy. According to the theory of ferromagnetic, the internal interaction energy of ferromagnetic material under the room temperature mainly includes: magneto-crystalline anisotropy energy E_K, magneto-elastic energy E_{ms} which is associated with the magneto-striction, and elastic energy E_{e1} only caused by deformation (Hubert (2011) reported).

Under the action of an external magnetic field, the increase of internal free energy in a single cubic crystal is due to the work carried out by the magnetic field, which is called magnetization work. The value of the free energy is associated with the direction of magnetization of the magnetic field. While the difference in free energy among different directions represents the difference of anisotropy energy along different axis directions. The general anisotropy energy within the crystal E_K, expressed in the form of a mathematical expression as:

$$E_k = K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2\alpha_1^2\alpha_2^2\alpha_3^2 \quad (5)$$

In the expression: K_1, K_2 – anisotropy constant;

α_1, α_2, α_3 – the cosine of the included angle between the magnetization vector and crystal axis.

The deformation energy inside the crystal consists of two parts. One is the magneto-elastic energy related to magneto-striction. Magneto-elastic energy can also relate to the magnetization vector, and it is anisotropy, then it can be derived by the formula of magneto-crystalline anisotropy energy (Vopson (2013) reported).

For example in single-crystal cubic system, the magneto-elastic energy E_{ms} can be derived by the following formula:

$$E_{ms} = B_1 \sum_i e_{ii}(\alpha_i^2 - \tfrac{1}{3}) + 2B_2 \sum_{i \neq j} e_{ij}\alpha_i\alpha_j \quad (6)$$

In the expression: B_1, B_2 – magneto-elastic coupling coefficient;

α_i, α_j – the cosines of the included angle between the magnetization vector and crystal axis;

e_{ii}, e_{ij} – deformation component (I,j = x,y,z).

The other part of the deformation energy is the elastic energy caused merely by the deformation. If the crystal is non-magnetic crystal, the position of the atom will move when the crystal deform, then elastic energy will produce. According to the elastic mechanics, elastic energy E_{e1} can be expressed as follows:

$$E_{el} = \tfrac{1}{2}C_{11}(e_{xx}^2 + e_{yy}^2 + e_{zz}^2) + 2C_{44}(e_{xy}^2 + e_{yz}^2 + e_{zx}^2) + C_{12}(e_{xx}e_{yy} + e_{yy}e_{zz} + e_{zz}e_{xx}) \quad (7)$$

In the expression: exx, e_{yy}, e_{zz}, e_{xy}, e_{yz}, e_{zx}- six components of the deformation energy;

C_{11}, C_{44}, C_{12} - elasticity modulus.

When the magnetic crystal is not affected by external force, the total internal free energy E is:

$$E = E_k + E_{ms} + E_{el} \quad (8)$$

However, when the magnetic crystal is affected by external force, the work done by the stress must be considered into the total free energy.

If the total internal energy is under a steady state, as known, the strain tensor e_{ij} relate to the stress σ can be calculated by the formula, the stress energy E_σ in the magnetic cube crystal system after derivation can be expressed as:

$$E_\sigma = -\tfrac{3}{2}\lambda_{100}\sigma(\alpha_1^2\gamma_1^2 + \alpha_2^2\gamma_2^2 + \alpha_3^2\gamma_3^2) - 3\lambda_{111}\sigma(\alpha_1\alpha_2\gamma_1\gamma_2 + \alpha_2\alpha_3\gamma_2\gamma_3 + \alpha_3\alpha_1\gamma_3\gamma_1) \quad (9)$$

In the expression: σ- stress; γ_1, γ_2, γ_3- stress direction; λ_{100}, λ_{111} - magneto-striction coefficient;

For the material of magneto-striction isotropy, the equation can be simplified as follows:

$$E_\sigma = -\tfrac{3}{2}\lambda_s\sigma + \cos^2\theta$$
$$\cos\theta = \alpha_1\gamma_1 + \alpha_2\gamma_2 + \alpha_3\gamma_3 \quad (10)$$

In the expression: λ_s -saturation magneto-striction coefficient;
θ- the angle between the direction of stress and magnetization vector.
When ferromagnetic is under the load of external stress, the direction of the internal magnetization vector will deflect, which can restrain the increase of stress energy to a certain extent. But anyway, it still remains definite stress energy inside the ferromagnetic even after the stress relief. The residual stress is relatively small than the external stress, so the stress energy attenuating and the energy balance is broken again. It certainly causes that the internal magnetic elasticity weakens relatively and it is shown in the form of reduction of the surface magnetic field value. It is known that the residual stress in ferromagnetic will decrease gradually over time, so the magnetic signal value will attenuate gradually.

3.3 Experimental verification and error analysis
In order to verify the accuracy of the fitting curve, take another verified specimen having the same condition with the test specimen to conduct verification experiment. The verified specimen has an artificial defect in the middle section of 0.18mm wide and 0.5mm deep. Load at a speed of 1 mm/min to 40000 KN and keep the stress state for 1 minute. Off-line measure the surface magnetic field strength, switch on the equipment at a fixed time, measure and calculate the normal magnetic field strength every day. Summary data for 6 months get the following testing data table as show in Tab.2 and data change trend chart as show in Fig.5.

Table 2: Normal magnetic field strength testing data of verification experiment

Day(d)	1	2	3	4	5	6
Magnetic Value(A·m-1)	432.328	432.742	431.762	432.568	431.591	431.645
Day(d)	7	8	9	10	11	12
Magnetic Value($A \cdot m^{-1}$)	431.65	431.821	431.633	432.392	431.681	431.363
Day(d)	13	14	15	16	17	18
Magnetic Value($A \cdot m^{-1}$)	431.152	431.525	431.817	431.056	431.261	432.112
Day(d)	19	20	21	22	23	24
Magnetic Value($A \cdot m^{-1}$)	430.981	430.632	431.132	431.182	430.672	430.961
Day(d)	25	26	27	28	29	30
Magnetic Value($A \cdot m^{-1}$)	430.65	431.095	430.856	431.122	430.614	430.69
Day(d)	33	36	39	42	45	48
Magnetic Value($A \cdot m^{-1}$)	430.482	429.821	430.368	430.124	429.981	430.162
Day(d)	51	56	61	66	71	76
Magnetic Value($A \cdot m^{-1}$)	429.411	429.115	429.434	428.297	428.673	428.335
Day(d)	81	86	93	100	107	114
Magnetic Value($A \cdot m^{-1}$)	428.219	428.082	428.112	428.311	428.189	428.055
Day(d)	121	128	135	142	149	156
Magnetic Value($A \cdot m^{-1}$)	427.898	427.766	427.343	427.457	427.093	426.769
Day(d)	166	176	184			
Magnetic Value($A \cdot m^{-1}$)	426.562	426.328	426.286			

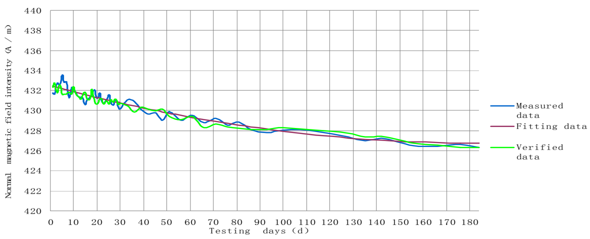

Figure 5: Verification experiment data comparison chart

By polynomial fitting function in MATLAB polyfit (x, y, n), the linear, quadratic and cubic polynomial fitting results are as follow:

$$y_1 = - 0.03366\ x + 431.78 \tag{11}$$

$$y_2 = 0.00015x2 - 0.05712\ x + 432.23 \tag{12}$$

$$y_3 = -1.16360\times10-6\ x3 + 0.00045\ x2 - 0.07648\ x + 432.46 \tag{13}$$

To analyze the result, it can find that the verified experiment and the initial experiment can acquire similar fitting result. So the attenuation model is suitable for this kind of specimen.
The experimental error contains system error, random error and fitting error.

The system error mainly includes earth magnetic field, equipment magnetic field and device error.
This experiment is needed to measure the surface magnetic field of the workpiece. All the magnetic elements will influence the result of the experiment.The earth magnetic field can influent, it can be subtracted from the surface magnetic field of the workpiece. By measuring the earth magnetic field value is 35 ~ 40A/m.
In addition, circumambient detecting instruments and data processing computers will form certain environmental magnetic interference, this kind of interference cause by the equipment can also be obtained by measurement. Equipment magnetic field value is 230 ~ 250 A/m in this experiment.
The detection signal value of EMS -2003 will change with the detection time owning to its hardware fever and the functional limitations of data processing module, so it will bring error. It is random error because of its uncertainty.
Process the experimental data by a polynomial fitting in MATLAB, select a curve closest to all the data as the fitting curve to express data law. In fact, it has a fitting error between measuring results and the fitting curve. This part is the fitting error of the result.

4. Conclusions

(1) It is found that the surface metal magnetic memory signal intensity could gradually weaken, by offline measuring a prefabricated artificial defect block specimen made of KMN material, it has certain timeliness.
(2) By using polynomial fitting to approach attenuation curve, an approximate quadratic polynomial fitting curve is obtained and a normal magnetic field intensity signal time domain model of KNM block specimen is built. This model can better correspond to the actual measuring signal.
In addition, this experiment also has its limitations. Only 6 months magnetic field data are collected, which presents a definite attenuation. According to the theory of metal magnetic memory and ferromagnetic analysis, the magnetic field signal could gradually stabilize and no longer decay after a period of time. Subsequently, it can continue to observe the surface magnetic field signal of specimen and make further research.

Acknowledgments

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