RESEARCH ARTICLE

Advanced Science Letters
Vol. 5, 1–5, 2012

Magnetic Memory Testing Method on Detecting Stress Distribution of Mechanical Components with Weak Ferromagnetism

Tu Qing-Song[1,*], Zhang Wei-Min[1], Chen Cheng-Feng[1], Li Hao-Yan[2], and Gao Xuan-Yi[2]

[1]*School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, China*
[2]*School of Automation, Beijing Institute of Technology, Beijing 100081, China*

A specific investigation on the corresponding connection between stress condition and external leakage magnetic field of carrying components with weak ferromagnetism subjected to heavy load-bearing situation in geomagnetic field is made in this disquisition. By the detailed analysis of the superficial magnetic signals, obtained by the metal magnetic memory testing technique, in the static tensile tests on bolted connections of two dissimilar materials, S45C and CuAl8Fe5Mn13 (weak ferromagnetic material) specifically, a phenomenon that the abrupt change of signals of CuAl8Fe5Mn13 certainly reveals stress concentration, though the mean amplitude of signals is much smaller comparatively, was found without effort. Subsequently, with supplementary magnetic signal processing and finite element analysis (FEA), a corresponding conclusion is not arduous to draw that evaluation of stress condition and detection of micro cracks on weak ferromagnetism components with metal magnetic memory (MMM) testing method is feasible.

Keywords: Metal Magnetic Memory, Weak Ferromagnetism, Stress Concentration, Finite Element Analysis.

1. INTRODUCTION

Resulting from its superior mechanical property, *CuAl8Fe5Mn13* is widely applied to manufacture components of high strength and great wear-resistance which is generally subjected to complex load both in industrialfield. It has been highly acknowledged that bolted connections, shaft sleeves and gears manufactured of *CuAl8Fe5Mn13* experience excellent strength, rigidity, and abrasion along with corrosion resistance. However, cracks generated in machining and forging process reduce compressive performance and service life by a big margin. Due to its weak ferromagnetism, the slight magnetic leakage signals of *CuAl8Fe5Mn13* components under load and external magnetic field are not strong enough for traditional electromagnetic nondestructive testing (ENDT) to make an exact evaluation. Fortunately, it is the sensitivity to extremely weak magnetic field that makes MMM become a new competitive nondestructive testing method for weak ferromagnetic materials such as *CuAl8Fe5Mn13*.[1–5]

2. SAMPLE AND MATERIAL

S45C of which mechanical performance is almost equivalent to *CuAl8Fe5Mn13* is utilized to manufacture ferromagnetic bolted connections in this experiment. The primary chemical compositions and corresponding mechanical performance of these two kinds of material are presented in Table I.

Four specimens fabricated of these two kinds of material are shown in Figure 1. In details, specimen 1 and specimen 3 are fabricated of *S45C* and specimen 2 and specimen 4 are made of *CuAl8Fe5Mn13*. They are all standard tensile specimens which are used to obtain particular mechanical property data and make a comparison straightaway. All *S45C* involved in this experiment had been addressed by 500 Celsius annealing heat treatment to remove the residual stress on the surface. Two bolted connections are standard triangular thread connections characterized by 1.75 mm pitch.

3. EXPERIMENTAL DETAILS

3.1. Tensile and Phenomena

The WDW-E1000, an omnipotent tensile testing apparatus controlled by computer, with 10^5 N rated load, was adopted in the experiment requiring 7×10^4 N load calculated approximately. Two practical tensile curves of these two kinds of material were obtained after tensile experiment for specimens 1 and 2, just as shown in Figure 2.

According two tensile curves, for *S45C*, yield phenomenon occurred when load mounted up to 27 kN. Furthermore, *S45C*

*Author to whom correspondence should be addressed.

Table I. Chemical composition and mechanical performance.

Material	Chemical composition (%) C	Cu	Mn	Fe	Al	σ_b	$\sigma_s(\sigma_{0.2})$	Hardness
S45C	0.5	0.25	0.8	96	—	600	355	197
CuAl8Fe5Mn13	—	74	13	5	8	600	270	157

experienced a significant plastic deformation and a sequential disruption under 40 kN force. Comparatively, for aluminum bronze, the yield strength is approximately 21 kN and the ultimate strength is about 40 kN. Apparently the yield strength of *S45C* is slightly higher than that of *CuAl8Fe5Mn13*, but the ultimate strength of the former almost parallels that of the latter. Meanwhile there is no appreciable distinction between the maximum elongation rates for both kinds of material. Consequently, in the tensile experiment for two specimens with same structure but fabricated from two diverse kinds of material, specimens of *CuAl8Fe5Mn13* were easier to achieve yield point but almost ruptured under the same ultimate strength as specimens of *S45C*.

Specimens were extruded in succession by gradually applied loads according to the load-carrying capability. To get a superior recognition and investigation of magnetic memory signals, the load step decreased gradually with the ballooning load and touched the minimum when the load fetched ultimate strength, which has been distinctly indicated in Table II. Tensile curves of specimens 3 and 4, obtained in the tensile experiment, are shown in Figure 3.

According to tensile curves above, specimens 3 and 4 all have experienced plastic deformation under the respectively maximum force. In more specifically terms, the drawing performance of specimen 3 is characterized by a curve with the plastic deformation under 30 kN force and the disruption under 50 kN force.

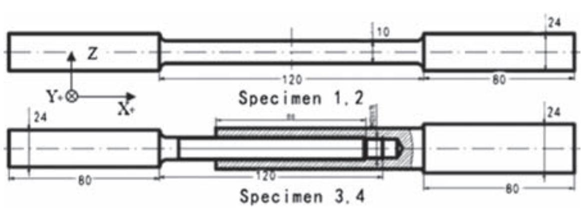


Fig. 1. Structural diagrams of specimens.

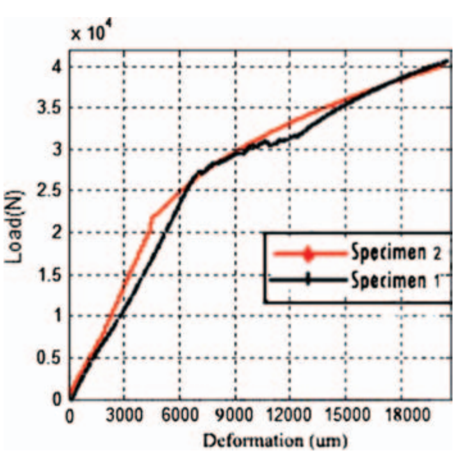


Fig. 2. Tensile curves of specimen 1 and 2.

Table II. Load steps for specimens 1 and 2 in details.

	Step 1 kN	Step 2 kN	Step 3 kN	Step 4 kN	Step 5 kN
Specimen 1	20	30	40	45	50
Specimen 2	20	30	40	45	50

Specimen 4 also experienced a conspicuous disruption under the ultimate force, 50 kN force. It is suggested that specimen 3 and 4 with the same structure, though fabricated from two diverse kinds of material, nearly shares the same mechanical property. Especially the almost identical stress and strain in the plastically deforming stage successfully caught our eyes.

According to the theory of magnetic memory, the eigenvalue of magnetic signals corresponds with stress concentration, especially in depth plastic deformation stage. At this moment, the significant magnetic flux leakage phenomenon occurs in the large-strain area due to the material accumulation of microscopic defect.[6] Therefore, the magnetic memory signals can determine the locations and levels of plastic damage on specimens.

3.2. Magnetic Memory Detection

The MMM-System TSC-3M-12, actually a two-dimensional magnetic memory tester, was utilized to observe weak magnetic memory signals H_x in the axial directions and H_z in the radial direction, also H_y in the tangential direction with 90 degrees revolving of the probe on its own axis. A measurement and storage execution concerning magnetic signals on the surface of the bolted connection in the vertical, tangential and axial directions followed every load intermission. Detection points locate at the root of screw thread with 1.7 mm spacing for specimens 3 and 4, and detection points of specimen 2 are concordant with the former two. Magnetic signals acquired are shown in Figures 4–6.

Specimen 2, a standard tensile specimen, experiences a uniform stress condition during the tensile process and an inevitable necking before the ultimate force. It can be conspicuously detected that a mutation of magnetic signals arose when necking emerged, though the signals, almost as slight as the geomagnetic field, were much weaker than those of steel 45. Especially the abrupt change of signals in the normal direction, z direction, under 50 kN force was so notable. Thus, magnetic leakage signals not only were produced under heavy load but also can characterize the stress condition of *CuAl8Fe5Mn13* similarly.

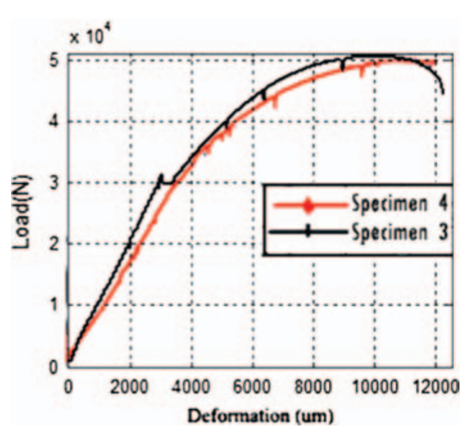
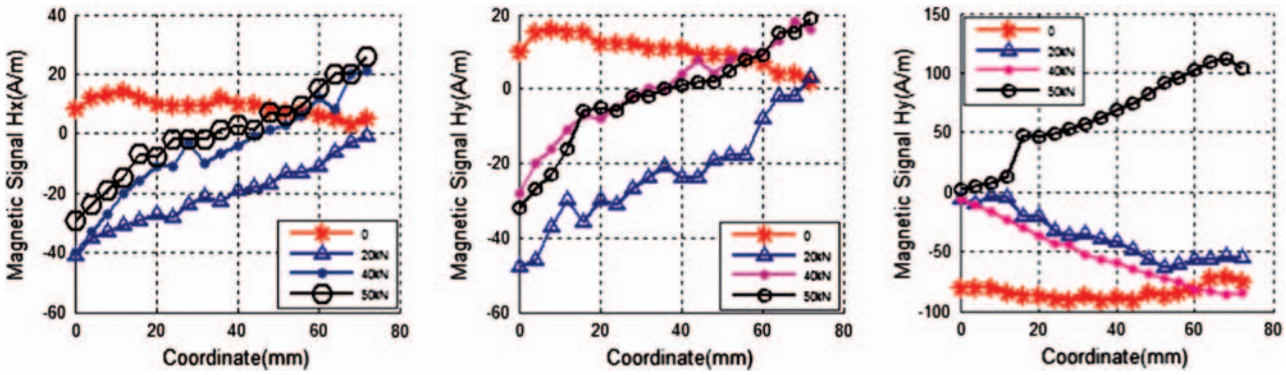
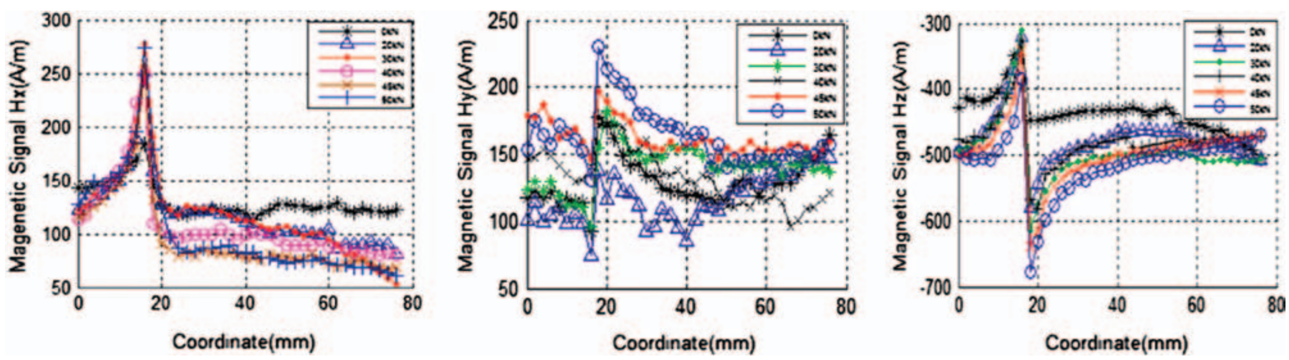


Fig. 3. Tensile curves of specimen 3 and 4.



Axial Magnetic Signal H_x Tangential Magnetic Signal H_y Normal Magnetic Signal H_z

Fig. 4. Three-dimensional magnetic memory signals of specimen 2.



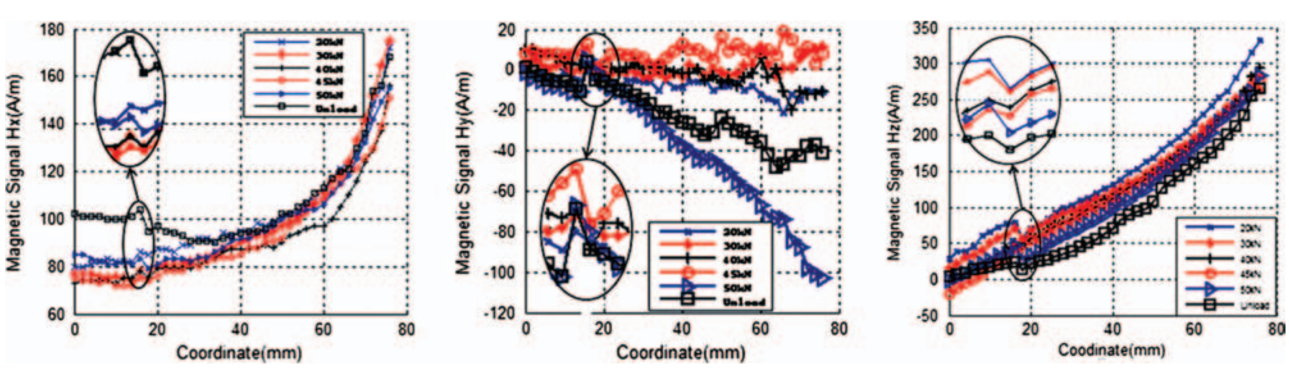
Axial Magnetic Signal H_x Tangential Magnetic Signal H_y Normal Magnetic Signal H_z

Fig. 5. Three-dimensional magnetic memory signals of specimen 3.

From Figure 5, with the accretion of load, a noticeable transformation arises at the ninth points. Specifically, H_x achieves the max value at this point while H_y and H_z mutate obviously. In comparison, for specimen 4, signals in every direction tend to be slighter and are characterized by a smoother curve. Nevertheless an identifiable mutation at the ninth detection point can be observed though the partial enlarged view. The ninth point was found to be at the first engaged screw, where stress is prone to concentrate.[7]

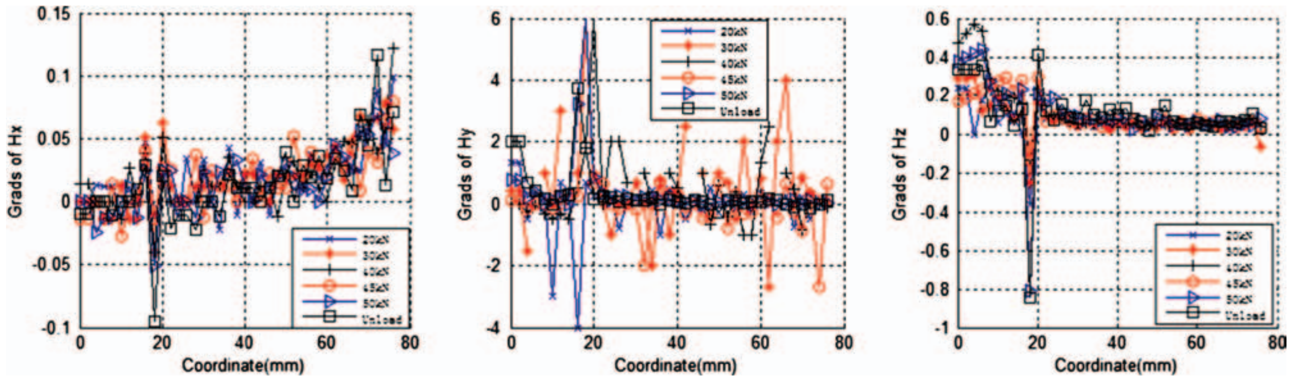
4. MAGNETIC SIGNALS ANALYSIS

From a comprehensive perspective, conclusion can be made that for specimen 2 fabricate of *CuAl8Fe5Mn13*, magnetic leakage signals were much slighter but can manifest the actual stress condition. Furthermore, for specimen 4 of the same material of specimen 2, magnetic signals distinctly depict the stress concentration around the first engaged thread. All these definitely demonstrate the feasibility of magnetic memory testing on stress condition of *CuAl8Fe5Mn13*.



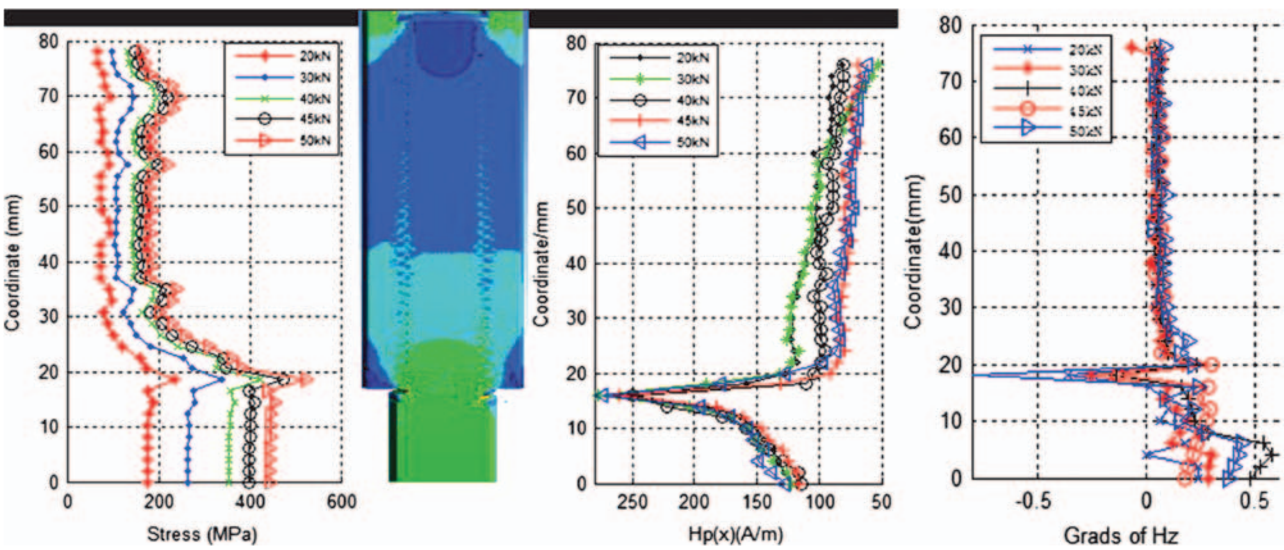
Axial Magnetic Signal H_x Tangential Magnetic Signal H_y Normal Magnetic Signal H_z

Fig. 6. Three-dimensional magnetic memory signals of specimen 4.



Axial Magnetic Signal H_x Tangential Magnetic Signal H_y Normal Magnetic Signal H_z

Fig. 7. Graded distribution of three-dimensional magnetic signals of specimen 4.



(a) Stress (b) Specimen model (c) H_x of specimen 3 (d) H_x of specimen 4

Fig. 8. Contrast between graded distribution of H_x and stress condition.

To delve the mutation, magnetic signals of specimen 4 was addressed by the equation below:[8]

$$H_i' = \frac{H_{i+1} - H_i}{H_i}, \quad i = 1, 2, \ldots, n \tag{1}$$

where H_i, H_{i+1} is the magnetic value of point $i, i+1$, respectively. This transformation decreases the measurement error to a certain extent and makes the mutation more conspicuous, the transformedvalue H_x', H_y', H_z' areshown in Figure 7.

According to Figure 7, the gradient value of signals on the ninth point of specimen 4 wasvery strong, which has effectively highlighted the mutative features of magnetic memory signals in weak magnetic materials.

5. FINITE ELEMENT ANALYSIS (FEA)

Throughthe contrast between the internal stress distribution obtained by finite element analysis and magnetic signals acquired by magnetic memory testing method of two specific bolted connections, the sensitivity of this innovative nondestructive testing to stress concentration is not tough to be recognized. The contrast between stress condition and magnetic signals in the axial direction H_x is shown in Figure 8. The more applied tensile load, the more prominent phenomenon that magnetic signals represent the stress distribution. The connection between stress and magnetic field whether for the bolted connection suffered half cut-off or the intact bolted connection is so evident that could declare the feasibility of magnetic memory testing on evaluating stress state for *CuAl8Fe5Mn13* components.

6. CONCLUSIONS

Mutative magnetic memory signals have been detected onspecimens made offerromagnetic materials *S45C* and weak magnetic materials *CuAl8Fe5Mn13* ingeomagnetic field. As the tensile loadson specimens increased, the magnetic leakage field in those places with great strain showed a significantregulation. In the experiment, we found that specimens fabricated from two diverse kinds of materialnearly share the same mechanical property and the same distribution of stress and strain when suffered from the same loads; therefore, it can be concluded that there should be an internal regularity that had caused the abnormal change of magnetic signals in those positions with great strain. Comparing specimen made of *S45C*, the magnetic memory signal of specimen made of *CuAl8Fe5Mn13* is much weaker; but after beennormalized, the features of these signalshave been enhanced. Through the finite element analysis of screw specimens, we found that the mutative positions of magnetic memory signalscorrespond withpositions with largestress concentration and large strain. This showed that magnetic memory testing methods can be used to precisely detect the stress concentration of bearing structure made of weakferromagnetic materials.

Acknowledgments: This research is financially Supported by the National Natural Science Foundation of China (Grant No. 50875023).

References and Notes

1. D. C. Jiles and J. B. Thoelke, *J. IEEE Transactions on. Magnetics.* 5, 3928 **(1989)**.
2. D. Minkov, Y. Takeda, and T. Shoji, *J. Appl. Phys.* 2, 74 **(2002)**.
3. A. A. Doubov, *Inspection Diagnostics* 6 **(2001)**.
4. B. Cullity, Introduction to Magnetic Materials, Addison Wesley **(1972)**.
5. D. C. Jiles and D. L. Atherton, *Appl. Phys.* 6, 17 **(1984)**.
6. D. C. Jiles and D. Utrata, *J. Nondestructive Evaluation* 3, 6 **(1987)**.
7. I. Korinm and P. Ipina, *J. International Journal of Fatigue* 2, 33 **(2011)**.
8. Y. Lin and S. Liu, *Advances in Imaging and Electron Physics* 77 **(2006)**.

Received: 18 April 2011. Accepted: 20 July 2011.