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RESEARCH ARTICLE

THE STUDIES ON CHARACTERISTICS OF MAGNETIC MEMORY SIGNALS OF FERROMAGNETIC COMPONENT FOR DOUBLE DEFECT ASSOCIATED

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ABSTRACT

Metal magnetic memory (MMM) testing technique is a novel testing method which can early test stress concentration status of ferromagnetic components. Adopting the combination method of experimental research and simulation analysis, and the influences of notch characteristics on magnetic memory signals were studied. In the experiment, the Q235 steel specimens with different defects were taken as the object of study, the mechanical characteristics of the static tension curve are studied, and the relationship between the magnetic memory signal with the tensile stress was studied. In the aspect of simulation analysis, under different tensile stresses, the distribution characteristics of stress and magnetic signal were simulation analyzed on different paths of double defect specimens, which is consistent with the test results basically. The results show that semicircular notch is more potential danger than V-shaped notch specimen; The normal component of magnetic flux leakage and gradient value in stress concentration of double associated notch specimen are no longer applicable for evaluating stress concentration degree of double associated notch. The conclusions are of great significance to the quantitative detection and further research of metal magnetic memory testing technology.

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INTRODUCTION

Structural and mechanical components manufactured with ferromagnetic materials are often subjected to fluctuating service load which are susceptible to cause failure as a result of fatigue (Zheng, 2001). Fatigue damage is one of the main forms of mechanical engineering component failure (Xu, 2005). The main causes of fatigue fracture are defects, grooves and their associated effects. The existence of the notch will affect the elastic deformation of material, shape deformation and fracture process (Ren *et al*., 2002; Holt *et al*., 1981). Stress-magnetism effect is magnetization changed caused by the internal stress changed (Abduallah and David, 2006). In recent years, the development of fracture mechanics provides a strong theoretical support for the damage tolerance design. Currently, the engineering structures and equipment were powered by damage tolerance design, which allows certain structures with initial defects, and still maintain a safe and reliable operation state in the provision life cycles. This thought of design not only ensures the service safety of engineering structural parts, but also avoids wasting lots of resources (Zhang and Zhang, 2007; Li and Ren, 2013). In addition, it is of great significance to timely monitor the fatigue damage state, to detect crack initiation and propagation, and to forecast the residual life of ferromagnetic components. Only the defect develop process was fully grasped, can we obtain sufficient warning information to avoid major failure accidents. At present, close attention has been paid on how to detect the fatigue crack accurately and stress concentration damage early, non-destructively, which is also a challenging task faced by both the non-destructive testing (NDT) industry and academy. Conventional NDT techniques, such as ultrasonic testing (UT), eddy current testing (ET), magnetic particle testing (MT) and penetrant testing (PT), etc., can only detect macroscopic flaws of certain size, but is powerless for the early damage and dynamic detection. Acoustic emission (AE) technique, as a dynamic NDT method, is effective to the early damage detection and dynamic monitoring. However, the AE method must be worked under loading condition, and its signals are difficult to process due to noise interference, which limiting the method to be used in a wide application (Dubov, 2012; Wang *et al*., 2010). Metal magnetic memory (MMM), which was first presented at the 50th International Welding Conference in 1997 (Doubov, 1998; Wilson *et al*., 2007) and originally developed by Russian researchers (Doubov, 2000; Doubov, 1997), is a new, nondestructive testing (NDT) and diagnostic method for assessing ferromagnetic material stress concentrations (Yang En *et al*., 2007; Doubov,2001) and fatigue damage. MMM technique is primarily based on the

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magnetic irreversible phenomenon that appears in stress concentrations and plastic deformation areas within ferromagnetic working pieces under load conditions. The method of metal magnetic memory testing makes use of the stress-magnetism effect of ferromagnetic materials, based on ferromagnetic materials under the function of working load and geomagnetic field, the inside domain organization orientation and irreversible orientation of a component formed leakage magnetic field in the stress, is one of the nondestructive testing methods for early diagnosis of the damage parts of ferromagnetic materials (Wang *et al*., 2010). In this paper, static load tensile test on containing different notch specimens, through extraction the normal component of magnetic flux leakage Hp(y) under different tensile load is carried, and the relationship between the magnetic field values at a fixed point with stress is studied. Carrying ANSYS simulation on double associated notch specimen, the internal stress distribution of double associated notch specimen and the relationship between the magnetic field value at a fixed point with stress are studied. The research results are of great significance to the quantitative detection and further research of metal magnetic memory testing technology

equipment is WDW-100 electronic tensile tester, its main parameters: the biggest test stress is 100kN, load error is ±(0.5%~1%), and loading rate of 0.3mm/min. When tensile stress reach the preset load value, then the specimen was taken from the tensile machine and make measurements. The specimen to be measured laid on the measuring platform in south to north direction, the normal component of the leakage magnetic field *Hp(y)* were tested along the determined path and fixed points of measurement.

The magnetic field strength value were measured used TSC-1M-4 type metal magnetic memory stress concentration indicator, measuring paths of in Fig.1. Fixed points A, B, C. Leakage magnetic field values were measured by LakeShore421 type weak magnetic field measuring instrument. Path1 was located in the specimen notch tip, path2 is from the notch tip of 2mm, path3 is in the middle of the specimen, the path is with a length of 100mm. The fixed point B was located at the center of the path3, A and C is 10 mm from the center.

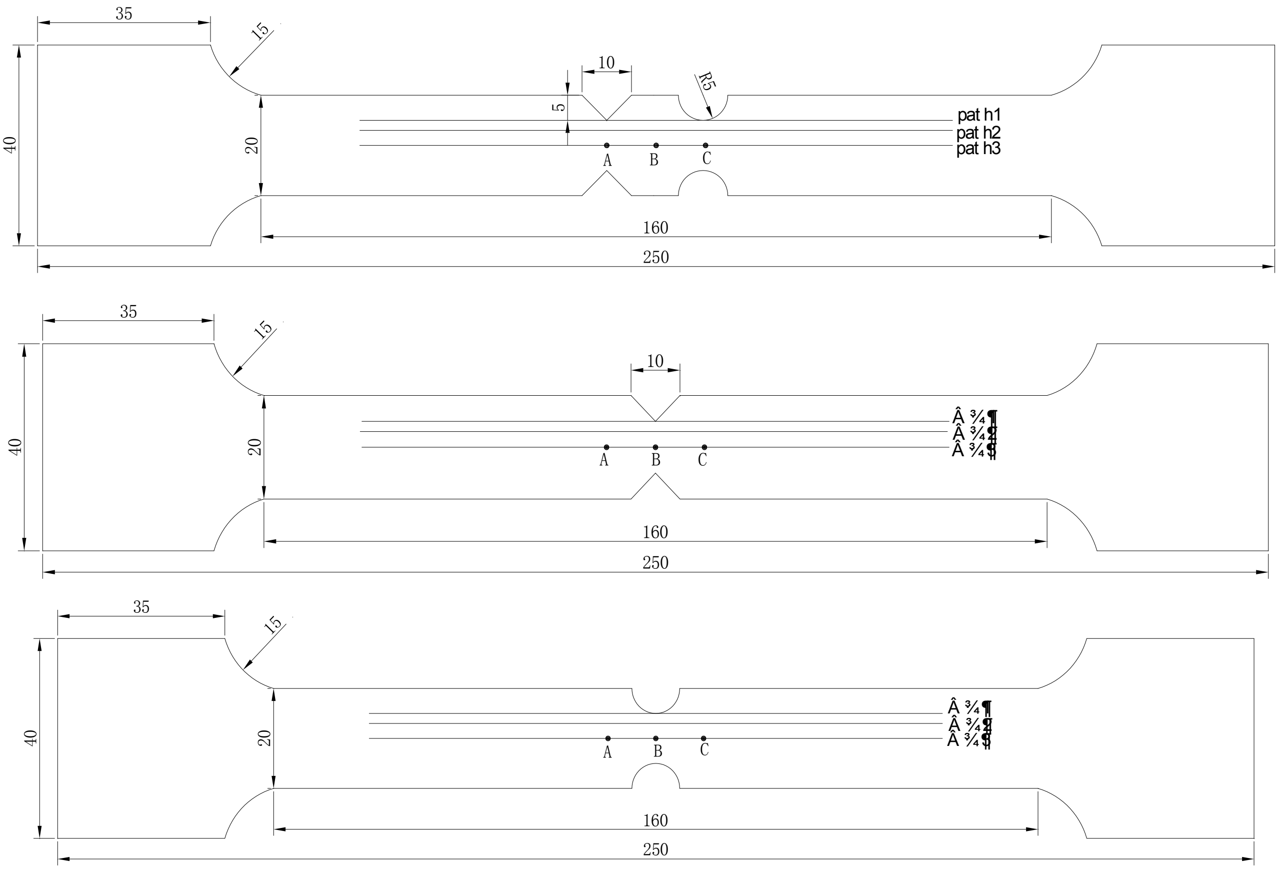


Figure 1. Diagrammatic sketch of three kinds notch specimens (thickness of 2.5mm)

Experimental and discusses

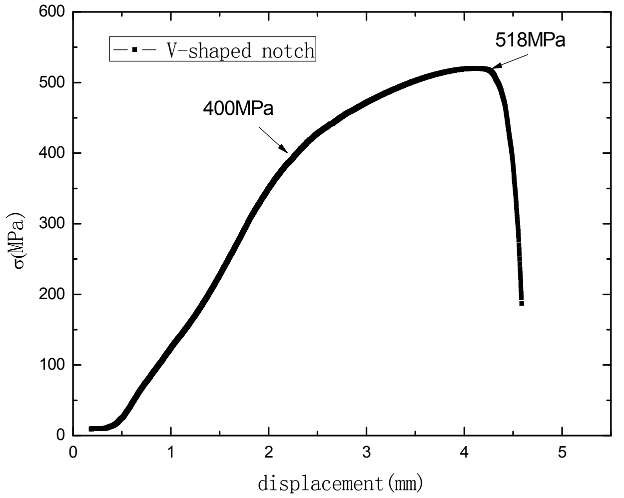
Experimental Method

The ferromagnetic specimens of Q235 ferromagnetic material were used in this experiment. This material is commonly used in the pressure equipment. Fig.1 presents one of the diagrammatic sketch of different notch specimens. In order to eliminate residual stress and magnetism when the specimen processing produced, the specimens were demagnetized and annealed before beginning the experiment. Tensile stress test

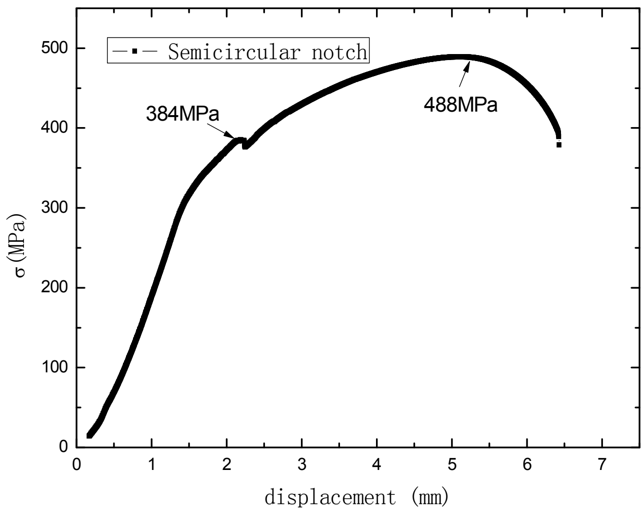
Experimental Results and Analysis

Stress-strain curves of three different notch specimens

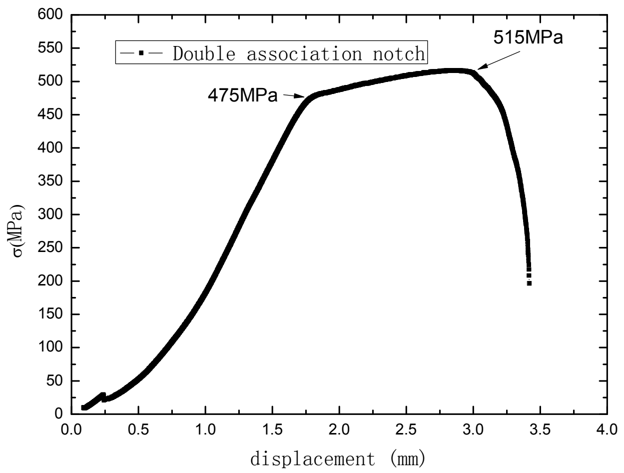
Fig.2 presents the stress-strain curves of three different notch specimens respectively. According to Fig.2, although materials are the same, the different notch specimens have different yield strength and tensile strength. The semicircular notch specimen is more easily fracture, and have more potential danger, the tensile strength of double associated notch more closer to the tensile strength of a single V-shaped notch, which is the result of the deformation caused by stress of the specimen. Since the existence of notch, the material strength increases, constrains plastic deformation of the material, reduces the material shaping, so shaping the material to be strengthened.



(a) The stress-strain curve of V-shaped notch



(b)The stress-strain curve of semicircular notch

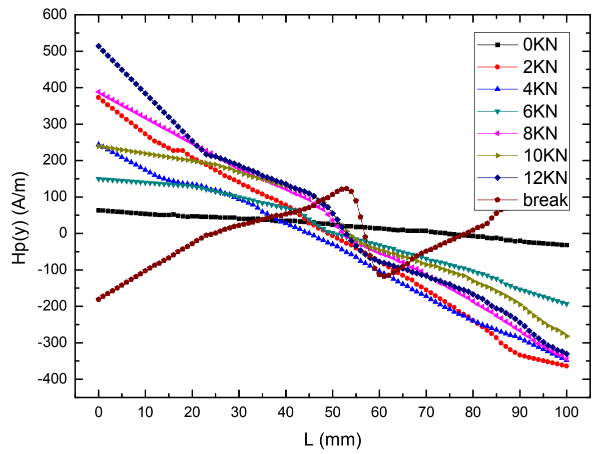


(c) The stress-strain curve of double defect associated

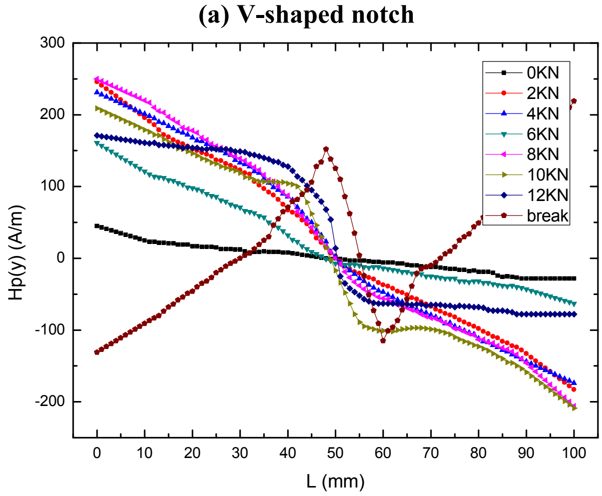
Figure 2. Stress-strain curve of three different notch specimens

The relation between the magnetic memory signal and stress for different notch specimens

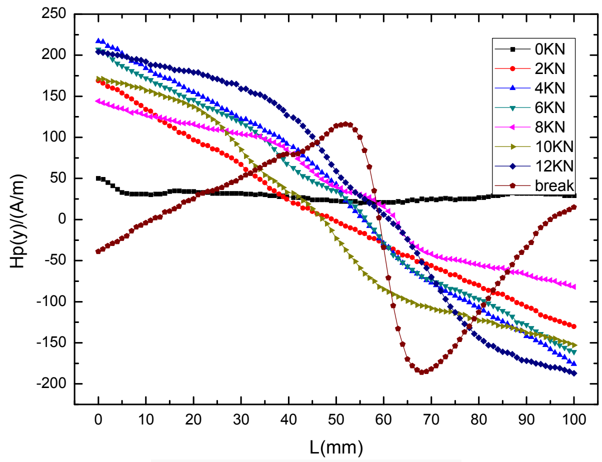
Fig.3 is the magnetic memory signal distribution curves of different notch specimens at different loads in path1. It is found that the magnetic signals of three paths were showed the same variation, only differ on the numerical value, So we only analyze the measurement data on path 1. Before experiment, specimens were demagnetized and annealed, so magnetic memory signal were almost approximate a horizontal straight line, the amplitude of the geomagnetic field was of (40A/m).With the load increases, the magnetic memory distribution curves became non-linear in stress concentration area, and the amplitude showed slow increasing. Before broken, all *Hp(y)* magnetic memory signal curves only have a zero value. Under the function of working load and geomagnetic field, the specimen is indeed magnetized, the specimen have positive and negative like a bar magnet, so the magnetic memory signal curve from positive to negative before fractured from positive to negative, and only have a zero point value. As shown in Fig.3c, the magnetic memory signal curve of double associated notch at the two gaps have occurred similar fluctuation, makes magnetic memory signal curve gradient increases slowly. Fig.3 shows that, before specimen broken, the V-shaped notch magnetic memory signal is stronger than the semicircular notch and double associated notch specimen, and the double associated notch specimen is the weakest; after broken, the interval gap between the maximum value and the minimum of V-shaped notch and semicircular notch specimen in the fracture is very approximate, but the interval gap between two extreme value point of double associated notch is larger relatively.



(a) V-shaped notch



(b) Semicircular notch



(c) Double associated notch

Figure 3. Magnetic memory signal distribution curve when different load

The relation of maximum gradient of magnetic memory signal with load

Fig.4 express the relation curve of between the maximum gradient magnetic memory signal of V-shaped notch specimen $|k|_{max}$ and load, $|k|_{max}$ defined as follows:

$$\left|k\right|_{\max} = \left|\Delta Hp(y)/\Delta l\right|_{\max} \qquad (1)$$

Where $\triangle Hp(y)$ is the difference between two adjacent points on the path , $\triangle l$ is the distance between the two points. As can be seen from Fig.4, with the increase of loads, the maximum of magnetic memory signal gradient, $|k|_{max}$, started a trend of slow growth, then increased linearly as specimen approached to be fractured.

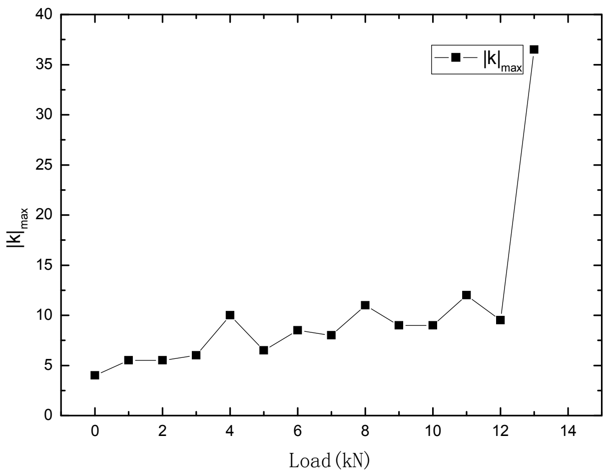


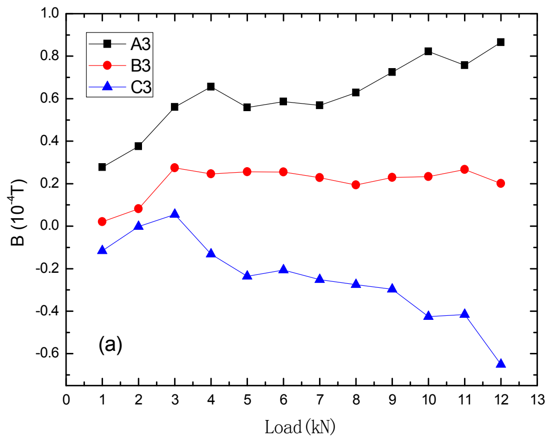
Figure 4. The related curve between $|k|_{max}$ and load

Figure 4 shows that at different stages of loading, magnetic memory signals show different. At the elastic deformation stage, due to the magneto-mechanical effect of the specimen caused magnetic elastic energy, the magnetic domain inside the specimen transformed from the initial disorderly state to the orderly state, magnetic slowly increased (Zhang *et al*., 2015). It can also be demonstrated, that the maximum of magnetic memory signal gradient $|k|_{max}$ slowly increased after entering the yield stage. Fig.5 express macro-photograph of the specimen broken. As can be seen from Fig.5 that the position of fracture of the double associated notch is on the semicircular notch. It shows that Although the magnetic signal of semicircular notch is weak, it is the easiest to break.

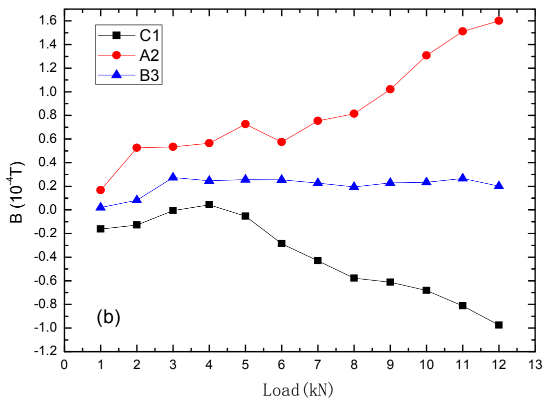
Figure 5. Photograph of the specimen fractured

The relationship of magnetic memory signal and tensile stress at certain point

In order to investigate whether the notch characteristics have an impact on magnetic memory signals, the A, B and C points taken from different notch feature samples are analyzed.



Leak magnetic field versus applied tensile load for double associated notch



(b) Different notch characteristics specimens fixed point magnetic field versus applied tensile load

Figure 6. The Relationship of leakage magnetic field value and applied tensile load at fixed point

Fig. 6a is the variation curve of the magnetic induction intensity versus tensile stress at the three measurement points (A3, B3, C3) for the specimen of double associated notch. It can be seen that the leakage magnetic field values of B3 points can be approximately the sum of the leakage magnetic field values of A3 and C3 points. Fig.6b is three different notch characteristics specimens certain point magnetic field along with applied tensile load (C1 point located in right V-shaped notch specimens, A2 point located in the left semicircular notch specimens, B3 point located in double associated notch center). The results show that the central magnetic field value of double correlation notch is the superposition magnetic field approximately produced by double notch.

Studies on the influences of double associated notch on magnetic memory signals based on ANSYS simulation

ANSYS simulation method

By the static analysis of ANSYS simulation, the stress distribution and leakage magnetic field distribution of the loading model are studied. In order to save the computing time and the hardware resource of computer, only half of the sample is modeled and analyzed under the condition that the calculation accuracy is satisfied (Zhang *et al.*, 2014). In statics analysis, symmetric plane of the model was applied to displacement constraints, and the end face was applied to tension. In magneto-statics analysis, applying the external environment magnetic field is 39.8 A/m, which is about the size of geomagnetic field.

Simulation result and discuss

Simulation analysis of stress distribution on different paths of double defect specimens

Figure 7. express the stress distribution nephogram, and Figure 8 express the equivalent stress distribution curses, which is applied of 60MPa tensile stress. As can be seen from figure 7 and figure 8, the stress distribution nephogram of the V shaped notch is butterfly shaped, and the stress distribution nephogram of semicircular notch is elliptical, the semicircle notch make the specimen more easily broken and has greater potential danger, which is consistent with the fracture location of the test..With measuring path farther from the notch tip, the stress concentration degree is dwindle, and the stress distribution curve turn into three peaks from double peaks, as shown in Fig.8. On the center measuring line path 3, the stress concentration is weakest at point A(Fig.1), the stress concentration is weaker at point C, and is the strongest at point B. It shows that due to the interaction of the double defects, Where stress concentration is strongest is not necessarily near the defect

At a certain point, simulation analysis of the relationship of leakage magnetic field and the stress

Fig.9 shows variation curves of the magnetic field values at fixed points (A3, B3, C3) with stress, which is the middle measuring line for specimen. It shows that on semicircular notch side, the change of the magnetic field value is relatively larger than that of on V-shaped notch side, which means that semicircle notch have a greater sensitivity to stress. At point of B3, the magnetic field value is a sum of superposition from point A3 and point C3, which is consistent with test results. Compared with figure 8, it can be seen that Where the stress distribution is extreme, the magnetic signal is not always the maximum. It shows that according to the size of magnetic signals to quantitatively determine the status of stress concentration has obvious limitations for the multi-defect component.

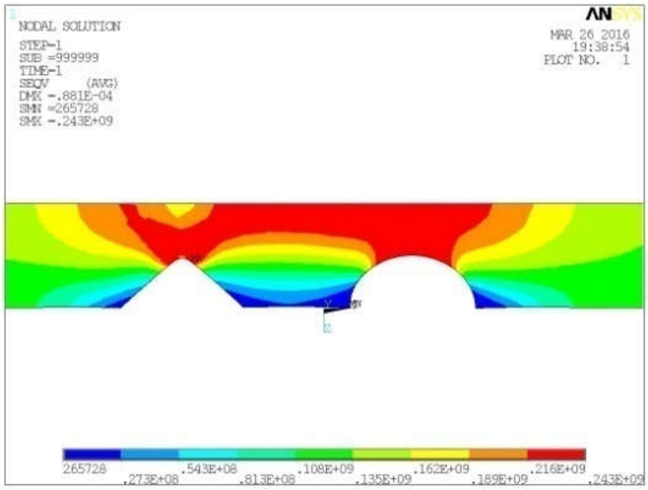


Figure 7. Equivalent stress distribution nephogram

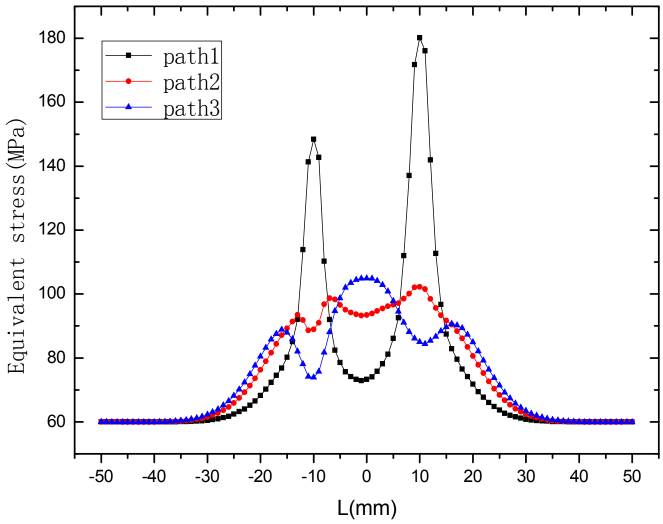


Figure 8. Equivalent stress distribution

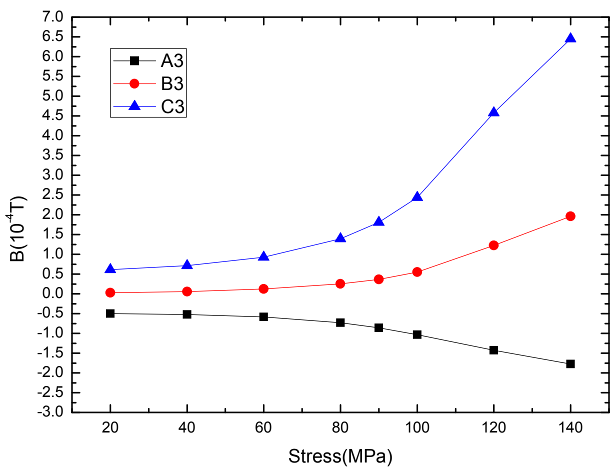
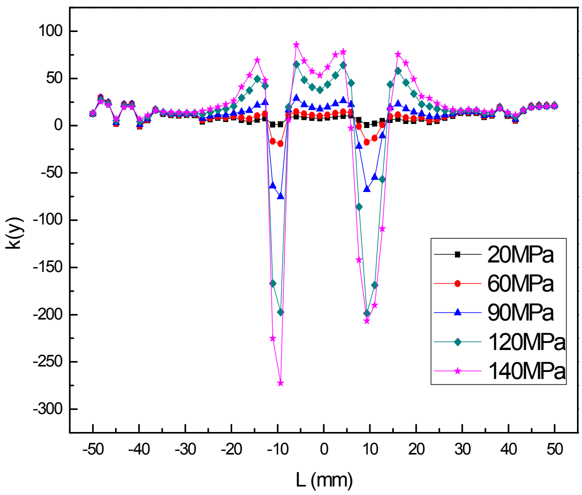


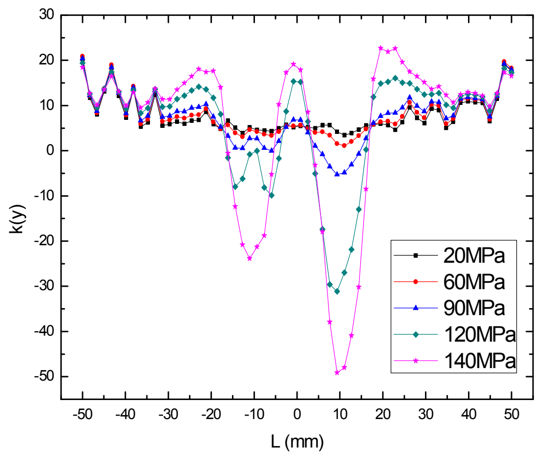
Figure 9. At a certain point the magnetic field value versus stress variation

Gradient distribution characteristics of normal leakage magnetic field on different paths

Fig.10 presents the gradient distribution of leakage magnetic field on path1 and path3 of component. At the V-shaped notch tip, the leakage magnetic field gradient value is bigger than semicircular notch on path1, as shown in Fig.10a, which indicate stress-magnetic effect of the V-shaped notch is stronger. The inner equivalent stress of V-shaped notch is distributed as butterfly, and stress distribution of semicircular notch is more concentrated than the V-shaped notch (Fig. 8). It shows that for the double defect specimens, where the maximum gradient of magnetic memory signal is the most, stress concentration is not necessarily the strongest. Fig.10b shows that the leakage magnetic field gradient of V-shaped notch on path3 turned into one peak from double peaks with increasing of tensile stress, the leakage magnetic field gradient of semicircular notch always increased with increasing of tensile stress constantly, which indicate that the stress-magnetic effect of the V-shaped notch is weaker than that of semicircular notch. It shows that for the double defect specimens, where the maximum gradient of magnetic memory signal is the most, stress concentration is the most dangerous probably. It can be concluded that to using magnetic memory signal gradient as a the stress concentration criterion is with obvious limitations for the multi-defect component



(a) path1



(b) path3

Figure 10. The gradient distribution of leakage magnetic field on path1 and path3 of component

Conclusion

The influences of double defect associated on magnetic memory signals for ferromagnetic component were studied. Specific conclusions are as follows:

(1) Different-shaped notch specimen have different yield strength and tensile strength, and semicircular notch have weaker magnetic field signals but have more potential danger than V-shaped notch specimen. The tensile strength of containing both V-shaped and semicircular double associated notch specimen is closer to the tensile strength of V-shaped notch specimen. The main reason is due to the deformation caused by stress of the specimen.

(2) Before specimen fractured, V-shaped notch magnetic memory signal is stronger than semicircular notch and double associated notch, and stress-magnetic effect of the double associated notch is the weakest. It shows that in a system with multiple defects, the place where magnetic memory signal is stronger is not necessarily the most vulnerable and dangerous place, however, the place where magnetic memory signal is not stronger may be the most easily broken and dangerous local.

(3) The interval gap between the maximum and the minimum value of V-shaped notch and semicircular notch specimen is very approximate in the fracture, but the interval gap between two extreme value point of double associated notch is larger relatively.

(4) In the middle stress concentration position of associated notch specimen, the normal component of magnetic flux leakage *Hp(y)* and its gradient value *k(y)* do not reach the maximum, so that making use of the result evaluating stress concentration degree of double associated notch are no longer applicable.

(5) With the increase of load, the maximum of magnetic memory signal gradient, $|k|_{max}$, started a trend of slow growth, then increased linearly as specimen approached to the fracture. The magnetic field values at the center of double associated notch is the result of the superimposed magnetic field values of a single notch corresponding approximate location.

(6) From the results can be seen that where the stress distribution is extreme, the magnetic signal is not always the maximum. It shows that according to the size of magnetic signals to quantitatively determine the status of stress concentration has obvious limitations for the multi-defect component.

(7) It can be concluded that to using magnetic memory signal gradient as a the stress concentration criterion is with obvious limitations for the multi-defect component. The conclusions are of great significance to the quantitative detection and further research of metal magnetic memory testing technology.

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