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A mechanism study on influence of strong external magnetic field on fracture properties of a ferromagnetic steel

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Abstract

For some ferromagnetic metallic materials, measurable influence of strong external magnetic field on their fracture properties has been observed experimentally, i.e., an external magnetic field of large intensity can promote the propagation of the crack. In order to clarify the mechanism of this phenomenon, a fracture model is put forward in this paper based on reversal magnetic domain theory and minimum free energy algorithm and verified through observations of magnetic domains structure. Compact tensile (CT) specimens which were stretched in strong magnetic field are adopted to observe their magnetic domains structure with the powder grain method in practice. It is found that the crack in the CT specimen propagated mainly along the magnetic domain wall rather than passing through the domain body. Together with the experimental results, the fracture model for the rupture and propagation mechanism under strong magnetic field was discussed.

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To clarify the influence of strong external magnetic field, which is indispensable in a magnetic confined nuclear fusion reactor, on the fracture properties of key structural materials adopted in the fusion reactors, experimental researches have been conducted in several research groups. Measurement results of rupture load in uniform magnetic field of direction perpendicular to the crack length shown that the environmental magnetic field could bring measurable influence on the fracture properties of these materials. References 1–4 give results on two kinds of stainless steel and Ref. 5 gives results on the China Low Activation Martensite (CLAM) steel. The CLAM steel is a kind of Reduced Activation Ferrite-Martensitic steel (RAFM) which could keep good mechanical performance under critical environment of fusion reactor. According to the fracture experimental results in Ref. 5, the critical fracture force of the CLAM steel reduced significantly once a strong external magnetic field was applied. This new phenomenon is very important for the design and safety evaluation of future nuclear fusion reactors, as the conventional design without considering this effect may lead to a structural safety problem. In order to understand the mechanism of this phenomenon, researchers have put forward several mechanism explanations, e.g., the phase transformation from austenitic to martensitic phase, but there is no direct evidence observed yet to prove the explanation. Little attention has been paid on influence of the external magnetic field on fracture mechanism of a ferromagnetic material. In this paper, a new hypothesis is proposed based on the minimum free energy theory and its feasibility is studied through experimental observations of the magnetic domain structures of specimen ruptured in environment of large magnetic field.

For magnetic materials, the magnetic properties, e.g., the magnetostrictive effect, can be described by the reversal magnetic domain theory. The magnetic domains inside the material are spontaneously magnetized and will be rotated in an external magnetic field according to the minimum free energy principle. The polarities of the magnetic domains will turn to the direction of the external magnetic field fully when getting saturated. This rotation of domain may lead to a deformation in the material, which is usually called the magnetostrictive effect. To know the magnetostrictive property of the CLAM steel, tensile strain of CLAM steel under strong magnetic field was measured by authors and a constitutive relation was
The CLAM steel material shrinks along the direction of the applied magnetic field.

When there is no external magnetic field or it is not large enough to influence the magnetic domains, the polarities of the magnetic domains are in a random arrangement and neutralized in macroscopical scale. To make it easier to explain and understand for the problem described in this paper, we suppose that the shape of the magnetic domains is of oval which is usually adopted to explain the magnetostrictive effect with the magnetic domain theory. Hereafter, metallic materials with a shrink tendency in an external magnetic field is chosen as examples.

In Fig. 1, the ovals refer to magnetic domains and the arrow refer to the direction of polarity of each domain. When there is no external magnetic field, the orientations of the magnetic domains are in a random arrangement. Figure 1 shows an extreme case of only toward up or down domain arrangement, which is the case of the largest magnetostrictive deformation in the horizontal direction, in order to explain the phenomena easier.

After applying an external magnetic field in the horizontal direction of Fig. 1, the polarities of the magnetic domains will turn to the parallel direction once the applied field is strong enough, i.e., over saturation field. As depicted in Fig. 2, because the polarity is along the minor axis of the ovals, the length of material in the horizontal direction will be shortened, which means a negative strain due to the external magnetic field. This theory gives good explanation on why some materials shrink in the external magnetic field, e.g. the CLAM steel. For materials with positive magnetostrictive strain, the polarity is along the long axis of the oval. So that after applying the external magnetic field, opposite situation occurs and positive strain appears.

In order to explain why the critical fracture force of the CLAM steel reduced significantly once a strong external magnetic field was applied, we raised up the following assumptions:

"The crack propagates more likely along the magnetic domain wall rather than pass through the domain body for a ferromagnetic material."

Based on this hypothesis, the phenomenon that strong magnetic field reduces the critical fracture force for the CLAM steel can be properly explained as follow:

As shown in Fig. 3 and Fig. 4, we consider the problem that the crack propagates along the vertical direction for the structure of magnetic domains in environment without and with strong external magnetic field, and suppose that the domain structure changes in a way the same as that depicted in Fig. 1 and Fig. 2. As negative magnetostrictive strain occurs for the CLAM steel, the dimension of the material in the field direction becomes smaller as shown in Fig. 4. By comparing the crack propagation routes shown in Fig. 3 and Fig. 4, one can find that the crack route is much more twisted before the strong external magnetic field was applied. A more twisted crack path means that the length of the crack route will be longer in the propagate direction. This reveals that more surface energy will be needed during the propagating process. In this way, we can answer the question why the critical fracture force will be reduced due a large external magnetic field.

The key point to validate the hypothesis given above is to find whether the crack propagates along the domain wall when it is in a strong magnetic field. It can be analyzed in the following points of view:
i) The minimum free energy principle for surface energy and magnetic energy.

ii) The high magnetic domain wall energy.

For point i), we know that the arrangement of the magnetic domain follows the minimum free energy principle. The domain energy system mainly consists of the demagnetizing energy of magnetic domains and the surface energy of magnetic domain walls. If the size of the magnetic domains gets smaller, the demagnetizing energy of the whole system will be reduced, but the total surface energy will be increased. The summation of these two kinds of energy should be the lowest when the magnetic domains are in spontaneous arrangement. Thus in the region near the crack tip, the system energy will increase if the crack propagates through a magnetic domain body, as more surface energy will generate. This will not be conducive to the propagation of the crack. For point ii), the size of magnetic domains is much larger than the thickness of magnetic domain walls. The polarity from one magnetic domain to the next one is different, and the angle between these two polarities usually is 180° when the material get saturated. This reveals that the magnetic energy of materials inside the region of magnetic domain wall will be restrained in this narrow region of domain wall, which will make the structure of the magnetic domain wall highly unstable comparing to the structure of magnetic domain.

With the two reasons above, we believe that the crack will propagate between the two magnetic domains rather than pass through the domain body, i.e., propagate along the domain wall. To check the validity of the hypothesis, fracture experiments of specimens of the CLAM steel are conducted in strong magnetic fields and the domain structure observation is conducted. In practice, compact tensile (CT) specimens made of the CLAM steel were adopted for fracture experiments. The specimens were stretched inside a strong external magnetic field, and the crack opening displacement and the tensile force were measured at the same time. The fracture mode of this metal is type I and belongs ductile fracture.

For magnetic domain observation, the surface of the specimens was treated with metallographic polishing before the stretch experiment. After being stretched in strong magnetic field, a drop of magnetic powder gel was put on the region near the crack tip, and a piece of cover glass was covered on the surface. The specimen was then observed with an optical microscope.

The observation results with the powder grain method are illustrated in Fig. 5 and Fig. 6. This specimen was stretched in a 5 T external magnetic field. In order to verify the validity of the observation, the powder image patterns around the crack tip was taken several times with gels of different concentrations. The concentration of magnetic suspension gel in Fig. 5 is 1.5%, and the concentration for Fig. 6 is 3%. The large dark region in Fig. 6 is caused by the accumulation of magnetic powder. As the structures of the observed magnetic domains in Fig. 5 and Fig. 6 are just the same, one can say that the magnetic domain observation results are reasonable.

As depicted in Fig. 7, by increasing the contrast ratio of Fig. 5, the domain structure becomes more clear and easy to be distinguished. Compared with a typical domain structure named multi-branched domain which is depicted in the lower left corner of Fig. 7, the domain structure of the observation result has high consistent. It can be found from Fig. 7 that the domain structure of the CLAM steel is a kind of multi-branched domain, which is a typical kind of stripe-shaped pattern, the high directionality is conducive for the observation of the crack propagation.

The zoom in views focused on the crack tip of Fig. 5 and Fig. 6 is illustrated in Fig. 8 to show the magnetic domain structures around the crack tips. The gel concentration is 1.5% in Fig. 8a and 3% in Fig. 8b. The domain structure in these two figures are the same, but related to different surface structure. The definitions of the main crack branch and sub-branches in these two figures are different. Based on the domains structures along the crack propagation route shown inside the circle in Fig. 8b, one can find that the directions of these domain structure are following the same direction of the crack route, which reveals the initial situation inside the external magnetic field. From this evidence, we can find that when propagating in strong external magnetic field, the crack route is most likely along the magnetic domain walls rather than passing...
through the domain body. In addition, one can observe that there are few domains teared up by a sub-branch of the main crack (circled in Fig. 8a). These sub-branches, however, finally stopped inside the magnetic domains. These two distinct evidences give support to the fracture model proposed in this paper, i.e., the main crack will propagate along the magnetic domain wall rather than passing through the domain body. The distribution of the domain structure around the main crack is in accord with our hypothesis and deductions.

It should be noted that the specimen was stretched in a strong magnetic field and observed without the external magnetic field. The arrangement of the magnetic domains will change after the external magnetic field being removed. We know that the propagation of the crack begins with the dislocations accumulated around the crack tip, thus the existence of dislocations around the crack route will prevent the rotation of magnetic domains around the propagation route, which will keep the initial domain structure to a certain degree after the external magnetic being removed. The domain structure outside the crack region is in spontaneous arrangement compare to the crack region as depicted in Fig. 5 and Fig. 6. This reveals the influence of dislocation on magnetic domains. Therefore, the observed domain structures can reflect the real situation when the crack propagated in the strong environmental magnetic field.

Though the metal adopted in this paper will gets saturated when the external magnetic field gets greater than 1.5 T, the increasing external magnetic field will still influence the rotation of the magnetic domains. The rotation of the magnetic domains is influenced by both the external stress and external magnetic field in the same time. The external stress will cause crystal deformation, which will bring variation on magnetic crystalline energy, then lead to the rotation consequently. The increasing magnetic field will bring increasing magnetic energy to resist the variation on magnetic crystalline energy. According to the magnetostriction experiment results of the CLAM steel, this deduction can be verified.

In this experiment, specimens of the CLAM steel were installed in a specially designed stretch device, which can apply tensile force up to 3000 N. The stretch device was placed in the working space of an electromagnet, which can apply a constant external magnetic field up to 1 T. The magnetostrictive strain was measured by using a strain gauge which was pasted on the middle of the tensile specimen. The direction of the strain gauge is along the direction of the external magnetic field. The magnetostrictive strain is defined as the strain caused by external magnetic field (the strain caused by mechanical stress was removed). From the experimental results in Ref. 9, it can be found that the absolute value of the magnetostrictive strain decreases with the increasing tensile stress. As the magnetostrictive strain relates to the magnetic energy, this phenomenon reveals that parts of magnetic energy is balanced by the external tensile stress. This finding shows that the influence of strong external magnetic field should be considered even after the material gets magnetic saturated. With this citations, we believe that this observation results and deductions give support to our hypothesis for fracture mechanism in strong magnetic field, i.e., the crack propagates along the domain walls. The existence of the strong external magnetic field causes a relative flat crack surface, which can promote the crack propagation of the CLAM steel.

In conclusion, a fracture mechanism hypothesis, i.e., the crack mainly propagates along the magnetic domain wall, was proposed in this paper to explain the influence of the strong external magnetic field on fracture properties of the CLAM ferromagnetic materials. Based on minimum free energy principle and observation results of the magnetic domains in fracture specimen of the CLAM steel, evidences supporting this hypothesis were found. The microscopic image of domain structure observed after being stretched in strong magnetic field reveals that the cracks do propagate along the domain walls, and some crack branches pass through the domain body was stopped. The present finding is beneficial for studying fracture properties of the magnetic materials in a strong magnetic field.
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