Study on Mechanical Properties of crack Healing of low carbon Steel based on cyclic Phase Transformation Heat treatment

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Abstract: With the rapid development of materials, metal materials are used less and less, but at this stage, metal materials are still widely used, and iron and steel materials are the most widely used. Cracks often appear in the process of metal material processing and use, and these cracks will have a certain impact on the use of metal materials. The existence of microcracks will affect the mechanical properties of materials to some extent, but in most cases, the mechanical properties of materials will be greatly reduced, and in serious cases, metal materials will break directly in the process of use or processing. The crack healing process needed after the emergence of cracks can effectively change this situation, but so far, the research on metal crack healing is still not perfect. In this paper, taking the internal crack of low carbon steel as the object, the recovery of mechanical properties of low carbon steel by cyclic phase transformation heat treatment was studied. The results show that with the increase of the healing area, the microhardness of the area after crack healing also increases, and the tensile strength of the specimen also increases after the healing. When the healing area is similar, increasing the healing time and temperature will result in grain coarsening, resulting in the decrease of microhardness and tensile strength in the crack healing zone.

1. Introduction
Low carbon steel is a kind of iron and steel materials, and in the classification of iron and steel materials, low carbon steel belongs to carbon steel, and the classification of carbon steel is mainly based on the carbon content. Low carbon steel is a kind of steel material with low strength. In addition to low strength, low carbon steel also has the characteristics of soft texture. The carbon content of low carbon steel is 25% [1]. There are many ways to form low carbon steel, because after heating treatment, low carbon steel is easier to cool and well formed. In the welding process, low carbon steel is used in many aspects, because its weldability is better than other metals, and the welding effect is better [2].

Parts will fail in some cases, the main reason for this phenomenon is the generation of metal cracks in the metal and the propagation of metal cracks, which will lead to a rapid decline in the performance of parts [3]. Because of the importance of cracks on metal use and processing, the research of cracks has always been a very important direction in the research of metal materials. Sun Zhigang [4] found that most of the cracking direction of the crystal crack is the longitudinal crack along the center of the weld. In addition, this paper also puts forward some feasible measures to prevent crystallization cracks. Hu Zhe [1] and others have studied the problem of crack healing in metal materials, and the internal and external factors will play an important role in crack healing. Xin Ruishan [5] et al have studied the repair behavior of internal cracks in low carbon steel under high temperature conditions. N. Qbau [6] proposed...
that the deformed aluminum alloy has the characteristics of light weight and high strength, so the alloy is the most commonly used material in many engineering industries, but there are many problems related to hot cracks in the process of selective laser melting.

Estefanía Cuenca [7] studied the crack resistance of steel fiber reinforced concrete under the action of crystal admixture. The curves of nominal tensile stress and crack opening displacement are analyzed, the equivalent tensile stress of the material is determined, and the evolution of the material along the crack and healing cycle is evaluated. The results show that as the crack closure index increases gradually, that is, the crack can be closed effectively, at the same time, the effective binding ability between fiber and matrix will be greatly improved, and then the toughness of the material will be slightly improved.

2. Experimental preparation

2.1 Experimental materials
The material selected in this experiment is 10# low carbon steel rod with diameter 15mm. The chemical composition of the material is listed in Table 1 below, and the mechanical properties of the material are shown in Table 2.

| Composition | Fe  | C   | Si  | Mn  | S   | P   |
|-------------|-----|-----|-----|-----|-----|-----|
| Content     | 0.13| 0.28| 0.55| 0.01| 0.008|

| Tensile strength Rm/MPa | Yield strength Re/MPa | Elongation A/% |
|-------------------------|-----------------------|---------------|
| ≥410                    | ≥205                  | 28            |

2.2 Crack preparation
The main purpose of this paper is to study the mechanical properties of crack healing. If we want to study crack healing, we need to prepare a crack and study its mechanical properties after crack healing. The methods of crack preparation include plate impact method, bending pressure holding method, hydrogen corrosion method, fatigue test method and borehole compression method. The borehole compression method is more suitable for the test in this paper, that is to say, we can use the borehole compression method to prepare the cracks in the sample. Figure 1 is a schematic diagram of the sample preparation process.

![Figure 1. Schematic diagram of sample preparation](image)

First of all, at room temperature, the raw material is machined into a cylinder with a height of 35mm and a diameter of 15mm, and a through hole with a diameter of 2mm is cut through the cylinder in the axial center. Finally, the two ends of the plane are welded and sealed by a laser welder, which is an internal crack, and several groups of samples need to be made for comparative tests.

2.3 Crack healing

(A) Crack healing test of thermostatic heat treatment
The sample with prefabricated crack is put into the constant temperature furnace, and the holding time is calculated when the temperature rises to the specified temperature again. When the holding time
reaches the set value, the sample is immediately taken out of the furnace and cooled to room temperature in air.

(B) Thermal expansion test
First of all, the 10# steel should be machined into a cylinder with $\Phi 3\text{mm} \times 10\text{mm}$ size by the corresponding wiring cutting machine, and then a round hole with a diameter of 2mm and a depth of 2mm is drilled on the cylinder by a drilling machine. The thermocouple is then welded to the position of the hole before the thermal expansion test can be carried out.

(C) Crack Healing Test of cyclic Phase Transformation Heat treatment
The Gleeble1500-D thermo-mechanical simulator can be selected to carry out the actual test of cyclic phase transformation heat treatment needed in this paper.

Each cycle of cyclic heat treatment includes two stages: cooling and heating, first cooling stage, and then heating up, after reaching a certain temperature, heat preservation treatment. After the cyclic phase change heat treatment, the vacuum state is ended, and the sample is placed in the vacuum chamber to cool to room temperature.

2.4 Mechanical properties after crack healing
(A) Tensile property analysis test
Before the tensile test, it is necessary to use the wire cutting machine to cut the healed sample into the tensile sample needed for the experiment. And in order to carry out the control experiment, three tensile samples are needed for each kind of fish and process, and different test parameters are selected for each kind of sample to carry out the comparative experiment. It is worth noting that in the process of cutting and preparation of the tensile sample, the crack must be in the middle of the sample.

In this experiment, the tensile rate needs to be controlled at 0.5mm/min. The purpose of this experiment is to explore the effects of different healing processes and test parameters on the healing of the paper from the point of view of mechanical properties.

(B) Microhardness analysis test
The microhardness can give the corresponding results on the mechanical properties of the specimens after crack healing, and the comparison is different before and after crack healing. In this experiment, the Shimadzu HMV-2T microhardness tester is selected, and the 10 times objective lens of the equipment is used to select the most suitable measuring position for the test. A 40-fold objective lens is used to measure and calibrate the size and position of the indentation. The test parameters are as follows: the test load is controlled at 98mN and the loading time is about 15s.

3. Analysis of the purpose of the experiment
When there are cracks in the metal, the mechanical properties of the material will decrease to a certain extent, so some appropriate processes are needed to make the cracks in the metal material heal. There are two evaluation points for the degree of crack healing, the first is the original shape of the residual crack, and the second is the size and area of crack healing. The evaluation of macroscopic morphology plays an important role in evaluating the recovery of mechanical properties. If we want to evaluate the
macroscopic morphology objectively, we can first observe the surface morphology of the sample and then compare it with the surface morphology of the original matrix.

At the same time, attention should also be paid to the recovery of mechanical properties of metal specimens with cracks after crack healing. The samples also need to be treated and healed under different healing processes and healing parameters. The recovery of the microhardness of the crack healing zone, the matrix near the crack zone and the matrix far away from the crack zone, and whether the tensile properties of the samples can be restored to the mechanical properties of the original matrix or better than the matrix at room temperature were studied.

4. Recovery of microhardness
The following picture shows two different microhardness test positions.

According to the observation in the figure, it can be seen from (a) that the origin 0 is set on the center line of the crack, the distance between each test point is 10 μm, and the center line is positive on the left and negative on the right. In figure (b), the origin 0 is set on the center line of the crack, left positive and right negative, a total of 4. A test point with an absolute value of 5 μm is called a test point near the crack zone, and a test with an absolute value of 15 μm is called a test point far from the crack zone, with a total of 4 points.

4.1 Recovery of microhardness of constant temperature healing
After cyclic phase transformation heat treatment, the material is air-cooled, and the microstructure can be divided into three types: crack healing zone, matrix near crack zone and matrix far from crack zone. The following picture shows the microhardness bar chart of the tissue after constant temperature heat treatment of 60 min at different healing temperatures.
It can be seen that when other healing conditions remain unchanged, in the temperature range of 900°C-1100 °C, the higher the constant temperature healing temperature, the higher the microhardness of the crack healing zone, and there is a positive correlation between them. With the increase of the healing temperature, the degree of crack healing will also increase, and the healing area will be larger; and the microhardness will increase accordingly.

When the test temperature increases gradually, the microhardness of the matrix near the crack zone and far away from the crack zone will decrease to a certain extent. In the temperature range of this experiment, when the healing temperature reaches 1100 °C, it can be found that the decrease of microhardness is the largest, compared with other different temperatures. Under the condition that other conditions remain unchanged, with the increase of the healing temperature, the average grain size of the matrix will gradually increase and the hardness will decrease accordingly. At the healing temperature of 900°C and 1000 °C, the crack healing zone has not completely healed, and there are some holes in the matrix near the crack zone, but there are almost no cracks far away from the hot crack zone, the microhardness of the matrix far away from the crack zone is the highest, the hardness of the matrix near the crack zone is the second, and the microhardness of the crack zone is the lowest. When the healing temperature is 1100 °C, because the crack has healed completely, there is little difference in the microhardness between the crack healing zone, the matrix near the crack zone and the matrix far away from the crack zone, which means that the crack has healed completely and the microhardness has been restored to almost the same state as the matrix. The following figure shows the microhardness bar diagram of the crack healing zone, the matrix near the crack zone and the matrix far from the crack zone under different healing time after constant temperature heat treatment and air cooling at 1000 °C.

When other healing conditions remain unchanged, the microhardness of the crack healing zone increases at first and then decreases with the extension of the healing time of constant temperature heat treatment, and reaches the maximum at 90 min. When the healing temperature is constant, the healing degree of internal cracks will increase with the increase of time. At the same time, the healing area of the internal crack will also increase, so with the extension of time, the microhardness of the crack healing zone will increase. However, when the healing time reaches 120 min, the microhardness will decrease, and the microhardness of the crack healing zone will decrease slightly.

4.2 Recovery of microhardness of healing crack after cyclic phase transformation heat treatment

It can be seen from the figure that the microhardness of the crack healing zone increases gradually with the increase of the number of cycles. With the increase of the number of cycles, the degree of crack healing increases, and the area of crack healing increases, so the microhardness of the crack healing zone also increases.

It can be seen from figure 6 that the microhardness of the crack healing zone increases gradually with the increase of the number of cycles. With the increase of the number of cycles, the degree of crack
healing increases, and the area of crack healing increases, so the microhardness of the crack healing zone also increases. When the number of cycles increases, the microhardness of the matrix near the crack zone and far away from the crack zone will not change obviously, which can be considered to be basically in a stable state. It is also proved that the crack healing method after cyclic phase transformation heat treatment has no negative effect on the coarsening matrix grains during crack healing. When the number of cycles is less than 30, the microhardness of the crack zone is lower than that of the matrix near the crack zone and far away from the crack zone. When the number of cycles is greater than or equal to 30 times, it can be found that the microhardness of the crack zone is higher than that of the matrix near the crack zone and far away from the crack zone. The analysis of this phenomenon is due to the fact that the crack basically healed completely after the number of cycles reached 30.

By analyzing the changing trend of the broken line in figure 7, it can be concluded that with the increase of the number of cycles, the microhardness of the crack healing zone increases gradually, while the slope decreases gradually, that is, the increase of microhardness gradually decreases with the increase of microhardness caused by a single cycle. The reason is that cracks have different healing mechanisms in different healing stages, so the speed of crack healing in the healing stage is different, and the increasing rate of crack healing area is also different, therefore, the increase of microhardness at the crack center decreases with the increase of the number of cycles. At the same time, it can be seen that although the distance from the crack center is different, the microhardness of the matrix is not very different, and it can be considered that the microhardness of the matrix does not change with the number of cycles. The reason for this phenomenon is that with the increase of the number of cycles, the average grain size of the matrix grain will not change and tends to be stable gradually.

With the extension of the healing time, the microhardness of the crack healing zone increases at first and then decreases, when the healing temperature and the number of cycles also increase. Near the crack matrix and far away from the crack matrix, due to the grain coarsening, the hardness decreases with the increase of healing temperature and healing time.

5. Recovery of tensile properties

5.1 Recovery of tensile properties of healed cracks after constant temperature treatment at room temperature

As shown in figure 8, if the healing temperature is 900 °C, in a certain time range, with the increase of healing time, the degree of crack healing increases gradually, and the ultimate tensile strength of the material increases gradually. At the same time, it can be found that the growth rate of ultimate tensile strength decreases gradually, which means that the growth of ultimate tensile strength is slower and slower, which is due to the different crack healing control mechanism of constant temperature heat treatment in different time.
5.2 Recovery of tensile properties of crack healing at room temperature after cyclic phase change heat treatment

As shown in figure 9, the ultimate tensile strength increases gradually with the increase of the number of cycles, and when it reaches 30 cycles, the ultimate tensile strength increases to 525MPa. However, the growth rate of the tensile properties of the samples per unit time is gradually decreasing, so it can be concluded that the healing effect of single cycle heat treatment decreases with the increase of the number of cycles. There are different crack healing mechanisms in different stages of crack healing, which leads to this phenomenon. The first stage of crack healing depends on atomic diffusion and recrystallization, while the second stage of crack healing only depends on atomic diffusion, and the third stage only depends on atomic diffusion, so the growth rate of tensile properties will gradually decrease with time.

6. Conclusion
In this paper, the mechanical properties of 1mm low carbon steel were analyzed and tested by constant temperature heat treatment and cyclic phase transformation heat treatment. The main conclusions of this paper are as follows: when the healing area increases, the microhardness of the crack healing zone will also increase. When the healing area is similar, if we continue to prolong the healing time or temperature, the microhardness of the healing zone will decrease to a certain extent due to the coarsening of grains. But these aspects are also with the process of growth, the growth rate is also gradually slowing down. With the increase of healing time and temperature, the microhardness of the matrix will gradually decrease. When the healing area increases, the tensile strength of the sample will also increase. When the healing area is about the same size, if the healing time or temperature continues to increase, the tensile strength of the healing zone will decrease to a certain extent due to the coarsening of grains. At the same time, in the process of continuous growth, the growth rate will gradually slow down, and the tensile strength of cyclic phase change samples is obviously higher than that of constant temperature healing samples.

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