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Microstructure and mechanical properties of internal crack healing in a low carbon steel

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A B S T R A C T

The behavior of internal crack healing in a low carbon steel at elevated temperatures was investigated. The internal cracks were introduced into low carbon steel samples via the drilling and compression method. The microstructure of crack healing zone was observed using optical microscopy and scanning electron microscopy. The mechanical properties of crack healing zone at room temperature were tested. The results show that there are two mechanisms of crack healing in the low carbon steel. Crack healing is caused by atomic diffusion at lower temperatures, and mainly depends on recrystallization and grain growth at higher temperatures. The microstructural evolution of crack healing zone can be divided into four stages, and the fracture morphology of crack healing zone can be classified into five stages. At the initial healing stage, the fracture exhibits brittle or low ductile dimple fracture. The ultimate fracture mode is dimple and quasi-cleavage mixed fracture. Fine grain microstructures improve the ultimate tensile strength of crack healing zone, which is even higher than that of the matrix. The strength recovery rate is higher than that of the plasticity.

1. Introduction

Cavity-type defects such as cracks and voids are inevitable during the manufacturing process of heavy forgings. These defects will severely deteriorate the mechanical properties of heavy forgings. The ultrasonic flaw detection results have revealed that cavity-type defects are the major cause of waste products. Therefore, Healing cracks and eliminating cavity-type defects in heavy forgings will reduce waste and improve their lifespan, which have enormous potential economic benefits.

Griffith [1] proposed that material fractures are irreversible, while some narrow cracks could be healed at elevated temperatures. Crack propagation and healing are two contrary processes that occur in metallic materials. Extensive studies on crack propagation in metallic materials have been performed during the last decades [2–6]. Moreover, Fracture mechanisms of metallic materials have been clearly understood. However, investigations on crack healing in metallic materials are comparatively rare and still in the initial stage [7–9]. Recently, Nanocrack healing in nanocrystalline metals was investigated using molecular dynamics simulations by Xu et al. [10]. Their results showed that the generation and motion of disclinations by migrating grain boundaries could lead to complete healing of nanocracks. Nanocrack healing did not require any compressive loads and even occurred under monotonic tensile loading. Petrov et al. [11] studied void and crack healing in polycrystalline metals under uniform compression over a wide temperature range from room temperature to $0.77T_m$. They found that void and crack healing relied on dislocation mechanism under uniform pressure at room temperature, whereas the dislocation mechanism was transited to diffusion mechanism with increasing temperature. Song et al. [12] carried out investigations on submicron-scale void healing in an Al-Mg-Er alloy using in situ transmission electron microscopy and electron tomography, and proposed that lattice diffusion dominated the entire healing process. Hosoi et al. [13] analyzed the fatigue crack healing in stainless steel SUS316 by a controlled high density electric current field, and found that crack propagation was temporarily delayed in the healed specimen and thermal compressive stress led to the crack closure. Zhang et al. [14] studied the evolution of intergranular fatigue micro-cracks in iron during annealing, and considered microcrack shrinkage depended on diffusive healing. Cracks in pure copper and carbon steel could be healed at elevated temperatures [15]. Long crack healing might depend on a “separate healing” mechanism that transformed the crack into a row of tiny smooth cracks and round holes. Internal crack healing in 20MnMo steel was performed at elevated temperatures by a series of experiments using the modeling method

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[16,17]. Experimental results showed that recrystallization was the primary factor for eliminating cracks and cavity-type defects. Han et al. [18] considered that crack healing mainly depended on atomic diffusion, and divided the process of crack healing into two stages: void filling and grain growth.

For the currently known mechanisms of internal cracks in metallic materials, researchers have not yet formed a unified theoretical understanding. Studies on the restoration of mechanical properties after the crack healing treatment are rarely seen. Thus, to further understand the mechanisms of crack healing and quantitatively evaluate the healing degree, it is essential to carry out further research on the behaviors of internal crack healing.

In this study, a series of experiments on the internal crack healing in a low carbon steel were carried out at elevated temperatures. The microstructure and mechanical properties of crack healing zone were studied. The results provide reference and basis for further research on crack healing in metallic materials, and also on quality control and improvement in heavy forgings.

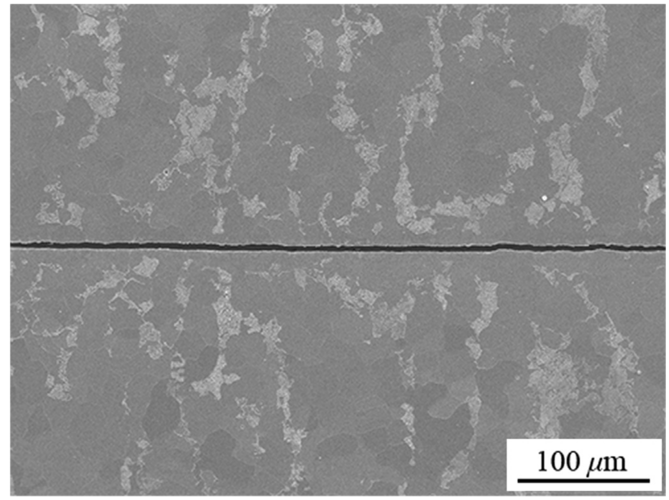

Fig. 2. SEM micrograph of the internal pre-crack.

2. Experimental procedure

The material used in this experiment was a low carbon steel, with the chemical composition (in wt%) of C 0.20, Si 0.29, Mn 0.58, P 0.009, and Fe the balance. Internal cracks were introduced into the samples via a drilling and compression method. Firstly, the steel was machined into cylindrical samples ($\Phi 40 \times 60$ mm). Then, a through hole of 2 mm in diameter was drilled in the middle of the side face of each cylindrical sample. The scraps inside the holes were removed via acetone and ethanol, and then the holes were sealed with M2 × 6 mm screws. The gaps between the screws and the samples were welded by laser welding. The cylindrical samples were subsequently heated to 800 °C for 30 min in the box resistor-stove, and then compressed with the reduction of 8 mm in height on a 50 t hydraulic press under ambient conditions, followed by water quenching. With these steps, as shown in Fig. 1, internal cracks were obtained in the cylindrical samples. Fig. 1 schematically illustrates the process of crack presetting, crack healing and tensile sample manufacturing.

Crack healing experiments were conducted at 900 °C, 1000 °C, 1100 °C, and 1200 °C over periods of 30 min, 60 min, 90 min, and 120 min, respectively. After the treatment, the samples were rapidly quenched in water, and subsequently sectioned along its longitudinal axis and perpendicular to the longitudinal axis of the original through hole. The sections were polished, ultrasonically cleaned and etched in a solution of 4% nitric acid and alcohol. The microstructure of crack healing zone was observed using an OLYMPUS-CX41 optical microscope (OM). A JSM-7100F scanning electron microscope (FEG-SEM) was employed to observe the morphological evolution of crack healing zone.

Based on Standard GB/T228-2010 [19], the tensile sample that was 5 mm in diameter and 50 mm in length was machined along the center of the healing sample, as shown in Fig. 1. To examine the restoration of mechanical properties, the crack healing zone was confirmed to lie in the middlemost part of the tensile sample. The tensile tests at room temperature were conducted at a tensile rate of 2.0 mm/min^{-1} on a WDW-100/E electrical universal material testing machine. A Zeiss Ultra 55 scanning electron microscope (FEG-SEM) was employed to observe the fracture morphology of crack healing zone.

3. Results and discussion

3.1. Pre-crack morphology

Fig. 2 shows the original morphology of the internal pre-crack. The crack width was about 4 μm at the length range of 20 mm in the center region of the pre-crack. However, the crack width ranged from 20 to 40 μm along the edge region of the pre-crack and near the screw. Thus, this study only focused on the central crack, and the edge crack was not considered.

3.2. Microstructural evolution

After etching the sample healed at 900 °C for 30 min in a

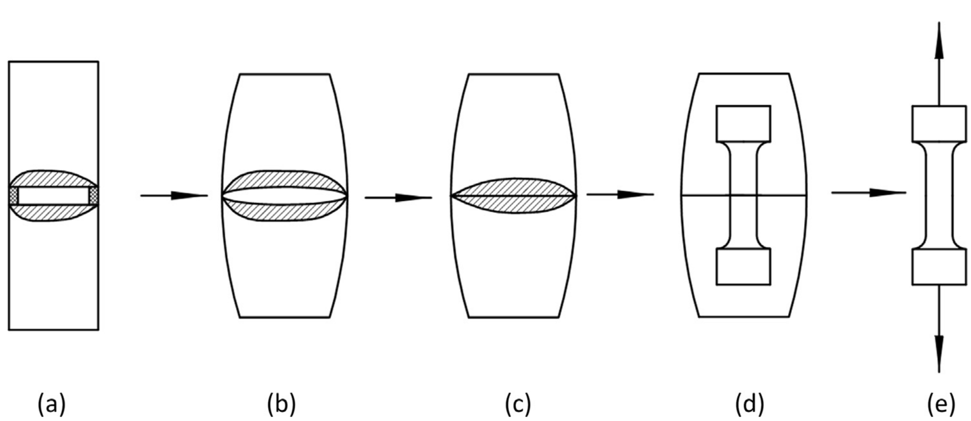

Fig. 1. Schematic illustrating the process of crack presetting, crack healing and tensile sample manufacturing: (a) drilling holes and sealing, (b) compressing, (c) healing and quenching, (d) machining tensile samples, (e) tensile testing.