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Variations in surface residual compressive stress and magnetic induction intensity of 304 stainless steel

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ABSTRACT

This study proposed micromagnetic nondestructive detection technology to detect the surface residual compressive stress of 304 stainless steel specimens after annealing treatment and loading. X-ray diffraction was used to determine the changes in residual compressive stress, microstrain, and grain size to aid in verification. Variations in surface residual compressive stress and magnetic induction intensity were analyzed. When residual compressive stress changed markedly, the change in magnetic induction intensity reflected the change in residual compressive stress. With the increase in residual compressive stress, the surface magnetic induction intensity and residual compressive stress of the specimen exhibited an approximate linear relationship, manifesting an increasing trend. Therefore, residual compressive stress was analyzed by detecting the changes in the surface magnetic induction intensity of specimens. Micromagnetic nondestructive detection allows the effective detection of the surface residual compressive stress of 304 stainless steel.

1. Introduction

During production, components bear the actions and effects of various factors. However, when these factors disappear, some of these actions and influences, referred to as residual stress, remain in the components. The presence of residual stress, to a certain level, exerts side effects on the material strength. These side effects include deformation, cracking, and other flaws from the manufacturing process undergone by the components. These side effects can lead to stress concentration and fatigue corrosion. Thus, the detection and control of residual stress are highly significant for the production and use of the components. 304 stainless steel is a Cr–Ni austenitic stainless steel with good mechanical properties, processability, and anti-corrosion capacity. This type of steel is widely used to manufacture equipment and parts with satisfactory comprehensive performance. This material is commonly used in aircrafts, turbine blades, nuclear power plants, gas turbines, petrochemical industry, pipelines, and other large equipment. However, 304 stainless steel also has severe problems of residual stress detection during production.

Mature residual stress detection methods include Mathar–Soete hole-drilling technique, magnetic measurement, and X-ray diffraction (XRD). The Mathar–Soete hole-drilling technique for measuring residual stress is widely accepted by engineers and scientists [1]. ASTM: E837 defines residual stress determination using the Mathar–Soete hole-drilling method [2]. However, this method can damage specimens, so it is classified as destructive detection. Magnetic measurements, such as the magnetic Barkhausen noise [3,4] and residual magnetic field measurements [5], are usually suitable for ferromagnetic components, so they are useless for 304 stainless steel and other non-ferromagnetic components. Among various nondestructive detection methods of residual stress, XRD [6,7] is universally acknowledged as the most reliable and practical one. With mature principles and perfect methods, XRD has been widely used in mechanical engineering and material science. This technique can measure residual stress and obtain the microstructure of materials. In the present study, XRD was used to verify the experimental data.

Numerous relevant studies on other nondestructive detection methods of residual stress have been reported. Resonant ultrasound spectroscopy (RUS) has been used to determine residual stress in small spherical balls. Measurement of resonant frequency by the RUS system and analysis of natural frequency effectively determine the values and distributions of unknown residual stress in spheres [8]. Variations in the velocity of ultrasonic waves are related to the residual stress state. Finite element modeling has been used to determine the capability and sensitivity of laser-generated ultrasound in residual stress measurement [9]. A novel approach called ultrasound interrogation was used to characterize the residual stress field in soft tissue [10]. Given the thick and large grains of austenitic stainless steel, ultrasonic waves cause serious dispersion and attenuation, which can lead to large measurement

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errors. High-frequency eddy current conductivity measurements can be used for the nondestructive evaluation of subsurface residual stresses in surface-treated nickel-based superalloy components [11]. The residual stress distribution has been measured in two girth-welded austenitic stainless steel pipe weldments using time-of-flight neutron diffraction; the results suggested the occurrence of stress corrosion cracking [12].

Micromagnetic detection is a nondestructive detection method that measures the changes in weak magnetic induction intensity on the surface of paramagnetic materials. Detection is conducted by a high-precision magnetic flaw detector under a natural geomagnetic field, and it further determines the existence of flaws on the surface of and inside the specimen. Micromagnetic detection can be applied in aluminum alloy, composite materials, and other paramagnetic substances [13–15]. On the basis of analyzing the magnetic characteristics of 304 stainless steel, micromagnetic detection technology was applied to detect the surface residual compressive stress of 304 stainless steel. The variation trends between residual compressive stress and magnetic induction intensity were analyzed. Comparative tests were conducted to verify the feasibility and reliability of micromagnetic detection. The proposed detection method is characterized by ease and speed of operation, as well as suitability for field or in-service detection.

2. Materials and methods

2.1. Materials

Composition segregation or improper heat treatment in smelting may cause few martensitic or ferritic structures in 304 stainless steel. Thus, 304 stainless steel exhibits weak magnetism. After cold working, the organizational structure of 304 stainless steel transforms into martensite. Strong cold working deformation results in more martensite transformation and great magnetism. High-temperature processing can recover and stabilize the austenite structure and further remove magnetism. Therefore, austenite 304 stainless steel possesses weak magnetism or paramagnetism, and this magnetic feature falls in the range of micromagnetic detection [12–14]. The specimen was a 2 mm-thick 304 stainless steel. Radiographic inspection was used to exclude disturbances of slag inclusion, air holes, cracks, and other flaws. The specimen was cut into two rectangular pieces of 285 mm × 50 mm (length × width). One piece was used for the heat treatment test (specimen 1), and the other was used for load testing (specimen 2). For convenience in operation and unnecessary edge interference, 10 points not close to the edge were marked symmetrically on the same positions of the two specimens as measurement points, as shown in Fig. 1. The residual compressive stress and magnetic induction intensity were measured on these points.

2.2. Methods

The test methods included heat treatment, loading, stress–strain measurement, and micromagnetic nondestructive detection.

The heat treatment mode used was annealing to eliminate part of the residual compressive stress. The annealing temperature was not set too high to observe a continuous decrease in the residual compressive stress with the change in annealing times. Once operation of annealing test is as follows. First, the furnace temperature was set to 500 °C with the maximum heating rate. Second, the specimen was placed in the furnace when the furnace temperature reached 450 °C. Third, heating was continued, and the temperature was maintained at 500 °C for 4 h. Finally, the specimen was removed from the furnace for air cooling when the furnace temperature dropped to 300 °C. The above annealing test was repeated with different heat preservation times (6, 8, 10, and 12 h) to produce varying effects of eliminating residual compressive stress.

Loading was conducted by applying different loads and loading times on the specimen surface to increase the residual compressive stress. The applied loads should be precise and not too high to observe a continuous increase in residual compressive stress. The applied loads can be set according to the approximate scope of the initial residual compressive stress of the specimen. These values are shown in Table 1. A stress 3000 X-ray diffractometer was used to determine the residual compressive stresses and mean grain sizes of the measurement points marked on the specimen. A D8 Advance X-ray diffractometer was used to measure the microstrain of the measurement points.

Micromagnetic detection was conducted under a natural geomagnetic field and free from an excitation source. A high-precision magnetic flaw detector was used to measure the magnetic induction intensity that was vertical to the specimen surface at the measurement points of the specimen. Micromagnetic measurement was implemented before heat treatment and loading, as well as at different periods of heat treatment and loading for follow-up data processing. An independently developed high-precision fluxgate sensor was selected as the magnetic measurement probe, with a measurement range of ±250,000 nT, resolution of 1 nT, and maximum sampling frequency of 1 kHz. The probe was set above the measurement points, and the magnetic induction intensity close to the specimen surface was determined.

3. Results and discussion

3.1. Variations in surface residual compressive stress and magnetic induction intensity after heat treatment

The corresponding magnetic induction intensity vertical to the specimen surface and residual compressive stress of each measurement point at different annealing times are shown in Fig. 2. In Fig. 2(b), the residual compressive stress of each measurement point before annealing was significantly greater than those after

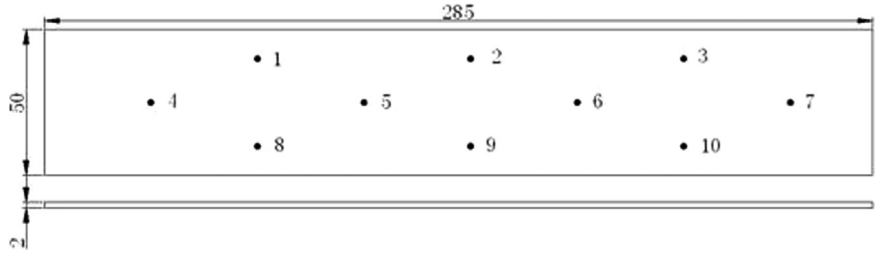

Fig. 1. Schematic of specimen and measurement points (unit: mm).