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Original Article

Effects on hardness and microstructure of AISI 1020 low-carbon steel processed by high-pressure torsion☆

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ABSTRACT

Low-carbon steel AISI 1020 was subjected to high-pressure torsion (HPT) with 6.0 GPa pressure through 1/4–5 turns. The microstructures of the samples in each turn were studied by means of X-ray diffraction (XRD) analyzing the changes in micro-strain, crystallite size and lattice parameter. Vickers testing was utilized to study the microhardness behavior of the samples subjected to HPT processing. The morphology evolution of the samples and especially the changes in ferrite and pearlite structures were studied for different numbers of turns using scanning electron microscopy (SEM).

1. Introduction

Low-carbon steel AISI 1020 is widely used as a construction material and for manufacturing of machine parts. Improving the mechanical and surface properties of this steel has been an important research field in materials science in the last decades because of its technological use. Usually, thermochemical heat treatments such as carbo-nitriding or boronizing have been used to improve the tribological behavior of AISI 1020 steel [1,2]. However, the use of severe plastic deformation (SPD) processes have shown important results in improving properties such as the hardness for this type of material [3].

High-pressure torsion (HPT) is a process that belongs to the SPD techniques. HPT is one of the most important and

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effective techniques for producing nanostructured and ultrafine-grained metals. In the HPT procedure, a disk-shaped sample is positioned between two anvils and then it is processed by applying simultaneously hydrostatic pressure and torsional straining, thereby modifying the internal structure of the material and achieving exceptional grain refinement even at the nanometer level. This processing also increases the hardness and leads to exceptionally high strength [4,5]. In this research, a low-carbon steel, AISI 1020, was subjected to HPT processing and the microstructural evolution, crystallographic behavior and changes in microhardness were studied.

2. Experimental materials and procedures

Cylindrical samples of 10 mm diameter and ~0.8 mm length of AISI 1020 steel were subjected to HPT processing. The samples were cut from a rod taken by machining from a block of AISI 1020 commercial steel. In order to relieve the stress introduced by machining, the samples were heated to 650 °C for 15 min. This thermal treatment introduced no change in the mechanical and structural properties of the samples.

The HPT process was performed at room temperature under quasi-constrained conditions [6]. The HPT equipment consisted of upper and lower massive anvils having central depressions with diameters of 10 mm and depths of 0.25 mm where the samples were placed. The rotation speed of the lower anvil was 1 rpm with a 6.0 GPa pressure. Two separate disks of the cylindrical samples were processed at $N = 1/4$, $N = 1$, $N = 2$ and $N = 5$ turns for measurements of microhardness and microstructural analysis [7,8].

Microstructural observations were carried out using scanning electron microscopy (SEM) in a JEOL model JSM 6490-LV. The disks were polished to have a mirror-like surface and then they were etched with nital solution. Images were taken at 10 kV near the sample edge positions at a distance of ~4 mm from the center of each disk. The microstructural behavior of the samples was studied by XRD diffraction using Panalytical equipment in a Bragg–Brentano geometry with Kα Cu radiation of wavelength $\lambda = 1.5406$ Å and with a step of 0.02° at 45 kV and 40 mA. An X'Pert HighScore computer program was used to index the diffraction patterns. The crystallographic analysis of the samples was performed by means of the Williamson–Hall model. In this model the full broadening of the diffraction profiles depends on three key factors; the crystallite size, the microstrain and the instrumental broadening [9,10] so that

$$\beta_f^2 = \beta_c^2 + \beta_s^2 + \beta_i^2 \tag{1}$$

Using the Scherrer equation, the crystallite size (β_c) and microstrain (β_s) contributions are given by, respectively,

$$\beta_c = \frac{K\lambda}{L\cos\theta} \tag{2}$$

$$\beta_s = \frac{4\xi\sin\theta}{\cos\theta} \tag{3}$$

where L is the volume average of the crystal thickness in the direction normal to the diffraction reflecting planes, ξ is associated with the microdeformation of the lattice and K is the Scherrer constant. In practice, $K = 0.94$ for full width at half maximum (FWHM) of spherical crystals with cubic symmetry and. β_i represents the instrumental broadening.

The lattice parameter was found using the Nelson-Riley function. From the Bragg law the lattice parameter for each peak reflection (hkl) may be calculated. Using the Nelson-Riley method, the lattice parameter corresponding to each peak was plotted against the Nelson-Riley function (NRF). The precise lattice parameter was taken from the intercept of the linear fit. The NRF function is given by [11,12]:

$$\mathrm{NRF} = \frac{1}{2}\left(\frac{\cos^2\theta}{\sin\theta} + \frac{\cos^2\theta}{\theta}\right) \tag{4}$$

The changes in the crystallographic orientation were analyzed by means of the orientation coefficient C_o. This coefficient quantifies the crystalline orientation degree in a particular crystallographic plane (hkl). The crystallographic orientation coefficient C_o is the relationship between the relative intensities of the most intense diffraction peaks and it is defined as [13]:

$$C_o = \frac{I_{(hkl)}/I_0}{\frac{1}{n}\sum_n^1\left(\frac{I_{(hkl)}}{I_0}\right)} \tag{5}$$

where $I_{(hkl)}$ is the largest relative intensity of the peaks of orientation (hkl), I_0 is the powder pattern sample intensity (taken from the X'Pert HighScore program with reference code: 01-087-0721) and n is the number of peaks.

The microhardness measurements were taken using an Esseway model 600 hardness tester at a load of 50 g-F and 25 s dwell time. In the preparation of the samples for the hardness measurements, the samples were encapsulated in epoxy resin and then they were polished to have a mirror-like surface. The measurements were taken at positions separated by 30 μm across the diameters of each disk, and each selected point is the result of four individual measurements taken around this position and separated by 15 μm from each other to form a square. Color maps of the hardness variation were plotted over the entire surface of the sample. The construction of these maps was performed by replicating 8 parallel lines uniformly distributed to cover the entire surface of the sample.

3. Results and discussion

Fig. 1 shows the XRD patterns of the samples of AISI 1020 steel processed by HPT. Typical α-Fe XRD patterns with reflections in the crystallographic planes (110), (200) and (211) are observed. The crystallographic orientation was analyzed for each sample using the orientation coefficient C_o which is shown in Fig. 2. The samples have a strong preferred orientation in the plane (110) and this orientation is accentuated when the HPT processing is performed.

The relative intensities of the peaks corresponding to the crystallographic planes (200) and (220) decrease with

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