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Strain-softening behavior of an Fe–6.5 wt%Si alloy during warm deformation and its applications

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ABSTRACT

An Fe–6.5 wt%Si alloy with columnar grains was compressed at a temperature below its recrystallization temperature. The Vickers hardness and structure of the alloy before and after deformation were investigated. The results showed that with an increase in the degree of deformation, Vickers hardness of the alloy initially increased rapidly and then decreased slowly, indicating that the alloy had a strain-softening behavior after a large deformation. Meanwhile, the work-hardening exponent of the alloy decreased significantly. Transmission electron microscopy confirmed that the decrease of the order degree was responsible for the strain-softening behavior of the deformed alloy. Applying its softening behavior, the Fe–6.5 wt%Si alloy with columnar grains was rolled at 400 °C and then at room temperature. An Fe–6.5 wt%Si thin strip with thickness of 0.20 mm was fabricated. The surface of the strip was bright and had no obvious edge cracks.

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1. Introduction

The Fe–6.5 wt%Si alloy is an excellent soft magnetic material with high permeability, low coercive force, and near-zero magnetostriction [1,2]. It has wide application prospects in transformers, power generators, and electric relay at high frequency fields [3]. However, because of its brittle property at room temperature, it is almost impossible to fabricate Fe–6.5 wt%Si alloys into thin sheets using a conventional rolling process [4]. As a result, its industrial application and development is seriously restricted.

Previous studies have reported that the workability of some brittle alloys, such as Ni_3Al, $Ni_{50}Al_{20}Fe_{30}$, and Al–Si alloy, can be improved by directional solidification. The main reasons for this improvement are the columnar grains produced by direction solidification. These alloys have less transverse grain boundaries, more reasonable shapes and distributions of plastic phases, and more low-angle grain boundaries, which can inhibit the propagation of cracks during deformation, unlike in the alloys produced through conventional casting [5–7]. In general, the intrinsic brittleness of an alloy at room temperature is related to the electronic structure and contents of the ordered phases. Considering the structural differences between Fe–6.5 wt%Si alloys and the brittle alloys mentioned above, investigation of the effectiveness of columnar grains for improving alloy workability is important. Zhang et al. [8] found that an Fe–6.5 wt%Si alloy prepared by directional recrystallization has excellent soft magnetic properties caused by low grain boundary energy and strong texture. Thus, accurately controlling the solidification or heat treatment process may be feasible methods to improve its soft magnetic properties.

On the other hand, it was reported that B element was effective in reducing the brittleness of some intermetallics at room temperature, because of its contribution to strengthen the grain boundary, reduce the antiphase domain boundary energy, increase the density of domain boundaries, and reduce the long-range order parameters as well as refine grains [9–11].

In this study, an Fe–6.58 wt%Si-0.05 wt%B (or also referred to as Fe–6.5 wt%Si alloy) alloy with columnar grains was fabricated using a directional solidification technology. Its Vickers hardness and order degree before and after deformation were investigated. The results provide insights into a better manufacturing process for Fe–6.5 wt%Si alloys.

2. Experimental procedure

An Fe–6.5 wt%Si alloy foundry alloy was prepared by vacuum melting and cutting into $\Phi 8\,mm \times 100\,mm$ rod by electric discharge machining. The rod was directionally solidified to obtain columnar grains using zone melting equipment. Solidification was carried out in an Ar atmosphere and cooled with water. The temperatures of the molten alloy and cooling water were about 1500 °C and 25 °C, respectively. The solidification rate (crystal growth speed) was 1.5 mm/min.

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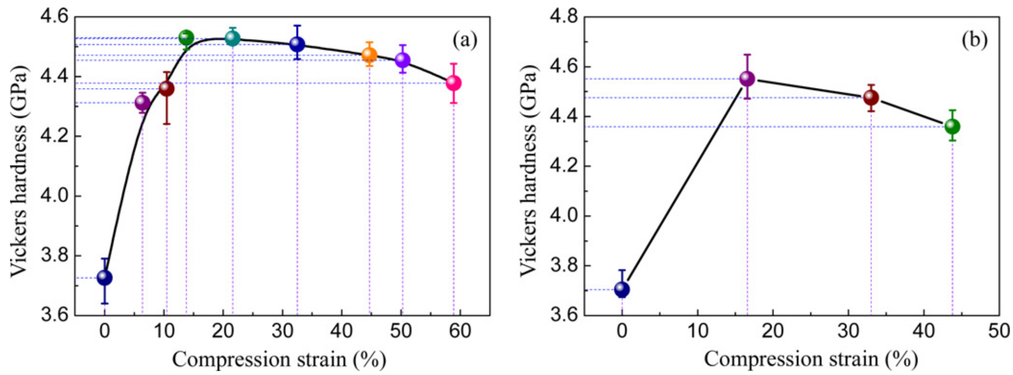

Fig. 1. Vickers hardness values of an Fe–6.5 wt%Si alloy (a) after single pass compression and (b) after multi-pass compression.

Rectangle samples of dimensions of 5 mm × 5 mm × 2.5 mm were from the ingot with columnar grains and compressed at 400 °C at a compression speed of 0.05 mm/s. The compression direction was perpendicular to the crystal growth direction. The compression strain was defined by the ratio of the thickness variation to the original thickness of the sample. Two compression methods were adopted in this study. The first method was the single pass compression. Samples were compressed with various compression strains using only one stroke. The second method was the multi-pass compression. Samples were compressed at a certain compression strain using several subsequent strokes. An HXD-1000T Vickers hardness tester was used to measure the Vickers hardness values of the samples. Standard deviation was based on seven measurements. JEM-200CX transmission electron microscope (TEM) was used to investigate the phase compositions and dislocation configurations of the original and deformed samples. The specimens for TEM analysis were electrochemically thinned by twin-jet polishing in a solution of 5% $HClO_4$/alcohol solution at 30 V and −20 °C.

3. Strain-softening and its mechanism

3.1. Strain-softening behavior

After single pass compression, the variation of Vickers hardness with the compression strain is shown in Fig. 1a. When the compression strain is less than 14%, hardness rapidly increases with an increase in the degree of deformation. When it exceeds 14%, the hardness slowly decreases. Compared with the compression strain of 14%, Vickers hardness is reduced by 3.3% at the compression strain of 59%.

The variation of the Vickers hardness of the sample after multi-pass compression is shown in Fig. 1b. Sample hardness increases drastically after the first pass compression (with a compression strain of 17%). The alloy exhibits obvious work-hardening. After the sample is subjected to further compression, its hardness begins to decrease slowly, and strain-softening behavior dominates the whole compression procedure. Compared with the first pass compression, the hardness of the sample is reduced by 1.7% and 4.2%,

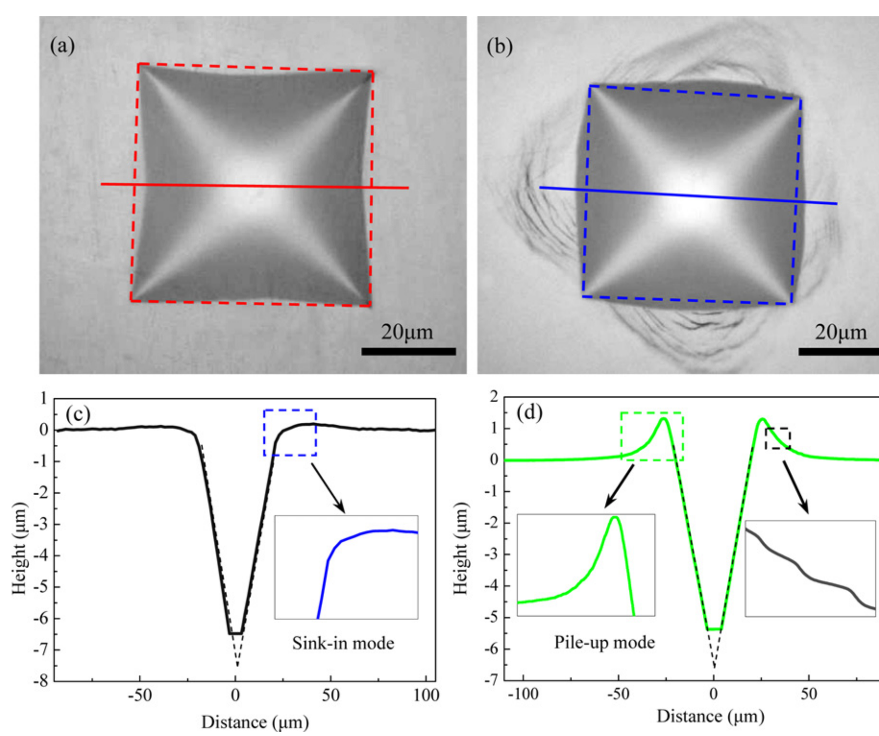

Fig. 2. Surface morphologies and vertical section profiles of micro-indentations: (a) indentation morphology of the original sample; (b) indentation morphology of the deformed sample (after three passes of compression, the accumulated compression strain is 44%); (c) section profile of the indentation in (a); and (d) section profile of the indentation in (b).

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