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Effect of 0.5 mass% Cu Addition on Ductility and Magnetic Properties of Fe-6.5Si Alloy

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Abstract: The effect of adding 0.5 mass% Cu on ductility and magnetic properties of Fe-6.5Si (mass%) alloy was investigated. The alloys with and without 0.5 mass% Cu addition were warm rolled into thin sheets of thickness no more than 0.3 mm at temperature below 600 ℃. It was found that the alloy with 0.5 mass% Cu addition was more easily warm rolled than Cu-free alloy. Tensile tests were carried out to further investigate this phenomenon, which confirmed that the ductility of the alloy with 0.5 mass% Cu addition was significantly higher than that of Cu-free alloy at 550 ℃. Based on the results of transmission electron microscopy analysis, the ductility increase of the alloy with 0.5 mass% Cu addition was attributed to the effect of Cu on the promotion of dynamic recovery and suppression of long-range order in the alloy during warm rolling process. It was also observed that the iron loss was lower and inductance was higher for the alloy with 0.5 mass% Cu addition. Thus, it can be concluded that adding a suitably small amount of Cu would not only increase the ductility of Fe-6.5Si alloy at warm rolling temperatures but also improve its magnetic properties.

Key words: Fe-6.5Si alloy; alloying; ductility; magnetic property; microstructure; long-range order

The best magnetic properties can be obtained for a silicon steel sheet with 6.5 mass% Si content. This Fe-6.5Si (mass%) alloy exhibits near-zero magnetostriction, high permeability and low iron loss at high frequencies, which are ideally suitable for the design and miniaturisation of a diverse range of energy-efficient electrical devices[1]. However, this alloy is brittle at room temperature[2,3]. As a consequence, it cannot be cold rolled to thin sheets for device applications, severely limiting its application potentials.

The brittleness of Fe-6.5Si alloy at room temperature is mainly attributed to the formation of the ordered phases B2 and $D0_3$[4,5] in a matrix of coarse grains during cooling[6]. A common approach to improving the ductility of Fe-6.5Si alloy is alloying so as to suppress the degree of the long-range order, refine the grain size of the matrix, or induce a combination of both effects. For instance, scholars[6-8] have reported that adding a small amount of B into Fe-6.5Si alloy could refine its grain size, which resulted in an increase in its ductility. However, B is an interstitial element, which may deteriorate the magnetic properties of the alloy[9]. Besides, alloying with substitutional elements seems to be a suitable approach to increase the ductility without reducing the magnetic properties of Fe-6.5Si alloy. However, the results reported in literatures so far are not conclusive. For instance, a number of studies have been carried out on the effects of alloying with Al, Ga, Cr and Ce and have shown that the ductility of high silicon steels can indeed be increased as a result of partial suppression of atomic ordering when one of these elements is added, but the magnetic properties of the alloys are also adversely affected[10-15]. Thus, further research is still required to identify alloying elements or mechanisms that would increase the ductility of Fe-6.5Si alloy without simultaneously worsening its magnetic properties.

It has been reported that approximately 2.3 mass%

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Cu can be dissolved in the Fe-6.5Si alloy at 800 ℃[16]. This is much higher than the solubility limit of Cu in α-Fe at the same temperature, which is approximately 1.8 mass% Cu[17]. It is thus considered that more Cu may be dissolved in Fe-6.5Si alloy than in α-Fe at lower temperatures. However, the effect of Cu addition on the ductility and magnetic properties of Fe-6.5Si alloy is unknown. The present study aims to investigate these effects. It is found that adding 0.5 mass% Cu into Fe-6.5Si alloy can improve the ductility and magnetic properties of the alloy simultaneously.

1 Experimental Procedure

The Fe-6.5Si alloys with and without 0.5 mass% Cu addition were produced by melting and casting in a vacuum induction furnace using industrial pure iron (99.5 mass%), silicon (99.99 mass%) and copper (99.9 mass%) as raw materials. The ingots were heated to 1150 ℃ and forged into slabs with thickness of about 20 mm. The slabs were then heated to 1000 ℃ and hot rolled to sheets with thickness of 0.8—1.0 mm. The hot-rolled sheets were heated again to 650 ℃ and then warm rolled in several passes to final thickness of 0.20—0.35 mm. In both hot and warm rolling processes, the steels were manually taken out of the furnace and fed into the rolling mill. The temperature drop of the sheets during this feeding process was much more rapid when their thickness became progressively thinner. It was estimated that the temperature of the sheets at the onset of the warm-rolling process was below 600 ℃.

Yield and fracture stresses as well as fracture strain were measured by tensile tests on a tensile testing machine (AG-IS 100 kN). Scanning electron microscopy (SEM, Nova 400 NanoSEM) was used to observe fracture surfaces of the specimens. Transmission electron microscopy (TEM, JEM-2010HT) was used to analyze the dislocation structure, and the selected area electron diffraction (SAED) patterns of the ordered phases were measured along the [001] zone axes. The core loss at 400 Hz (1 T) ($P_{10/400}$) and the magnetic induction at 5000 $\mathrm{A \cdot m^{-1}}$ (B_{50}) of the thin sheets produced were measured using an AC/DC magnetic measuring instrument (MPG-100D) from specimens with a size of 300 mm×30 mm×0.3 mm.

2 Results and Discussion

2.1 Effect of 0.5 mass% Cu addition on warm rolling behaviour

It was observed that, with the same rolling parameters and procedures, the alloy with 0.5 mass% Cu addition could be more easily warm rolled than the Cu-free alloy at temperatures below 600 ℃. For instance, the alloy with 0.5 mass% Cu addition could be warm rolled to sheets with thickness of 0.3 mm and width of 130 mm without the formation of any edge crack (Fig. 1). In contrast, the Cu-free alloy could be warm rolled to the same thickness free of edge cracks only when the width of the sheets was less than 90 mm. When the width of the sheets reached 90 mm, tiny edge cracks always occurred in the case of the Cu-free alloy as illustrated by the insert of Fig. 1, which shows the enlarged image of the edge areas indicated by the small circles. When the width of the sheets was larger than 90 mm, the Cu-free alloy could not be warm rolled to 0.3 mm in thickness without incurring great numbers of large edge cracks. These observations suggest that the ductility of the alloy with 0.5 mass% Cu addition was larger than that of the Cu-free alloy at temperatures below 600 ℃. This was confirmed by the tensile test results, as discussed in the following section.

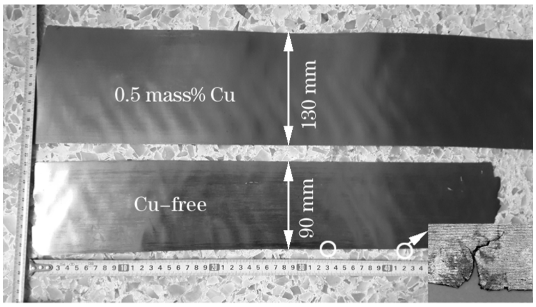

Fig. 1 Micrograph of warm-rolled Fe-6.5Si (mass%) sheets of 0.3 mm in thickness

2.2 Effect of 0.5 mass% Cu addition on tensile properties at 550 ℃

Tensile tests were carried out at 550 ℃ for both Cu-free and Cu-containing alloys on hot-rolled specimens of 1.0 mm in thickness; three separate tests were made for each alloy. The typical tensile stress-strain curves obtained are shown in Fig. 2(a). The yield stress and tensile stress of the Cu-free alloy were about 557 MPa and 560 MPa, respectively, while those of the alloy with 0.5 mass% Cu addition are about 512 MPa and 517 MPa, respectively. The strain of uniform deformation, i.e., the maximum strain at the onset of necking, was approximately the same at around 5% for both alloys, but the strain at fracture of the alloy with 0.5 mass% Cu addition (about 18.8%) was significantly higher than that of the Cu-free alloy