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The microstructure evolution of Fe-Si alloys solidified in a high static magnetic field

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Abstract:

The effect of magnetic field on the microstructure during the bulk solidification process of Fe-3*wt.*%Si alloys has been investigated experimentally. The results show that the ferrite turned into granular and bulk morphology as the increase of magnetic flux density (MFD). The microstructure in the region which is adjacent to the wall of corundum crucible was same in the samples with and without high static magnetic field (HSMF). When the MFD exceed 1.0 T, the ferrite was coarse. These phenomena were attributed to thermoelectric magnetic convection in solidification.

Keywords: Thermoelectric magnetic convection; Silicon steel; Solidification; Ferrite

1. Introduction

During solidification,most models of the formation of microstructure neglect the influence of convection and only consider diffusional transport of heat or mass away from the growing crystal. However, at low growth rates, ever bulk solidification process, convection and its influence on microstructure formation and development can become dominant [1.2] and should not be neglected. Indeed, Charborty et al.[3-7] have investigated numerically the effect of convection on the solidification structure during electromagnetohydrodynamic stirring processing, and have shown that convection will affect the solidification structure significantly. The effect of a permanent magnetic field on convection in solidification has been discussed extensively [8]. It has been determined that the application of a magnetic field during the directional solidification of materials can significantly reduce the thermosolutal buoyant flow [9-11]. Albousiere et al.[12] suggested that this new flow was induced by the interaction between the magnetic field and thermoelectric effects, and Lehmann [8] subsequently offered some experimental evidence for thermoelectromagnetic convection(TEMC).

It has been found that a high magnetic field causes the breakdown of needle-like ferrite into granular and bulk shape. Here, we propose a theory for the magnetization and TEMC of a binary alloy under a high magnetic field, and explain the breakdown of the needle-like α ferrite phase through this theory.

2. Experiment

The Fe-Si alloy used in this study were prepared with high-purity Fe (99.99wt.%), Si(99.99wt.%) in an induction furnace. The alloy were placed in a high-purity corundum crucible(4 cm diameter) and heated to a certain temperature (1520℃ for the Fe-3wt.%Si alloy,1540℃ for the Fe-1wt.%Si),then heat insulation for 10 min and cast specimens by suction casting. Φ8mm ×10mm rods were cut from the cast specimen and were enveloped in a tube of high-purity square corundum for the bulk solidification experiments. The experimental setup we used for the solidification is the same as that shown in Ref [13] and consists of a superconductor magnet, water-cooling cover, heating furnace and controlling temperature system. The superconductor magnet can generate a high magnetic field up to 8T. The furnace was set in the room bore of the magnet and the temperature in it could reach 1600℃.

Fig.1 shows the phase diagram of the Fe-Si alloy near Fe and the temperature profiles for the solidification procedure. The samples obtained from the experiment were cut along the direction parallel and perpendicular to the magnetic field. After machining off the surface, the longitudinal （parallel to the magnetic field direction) were examined in the etched condition by optical microscope.

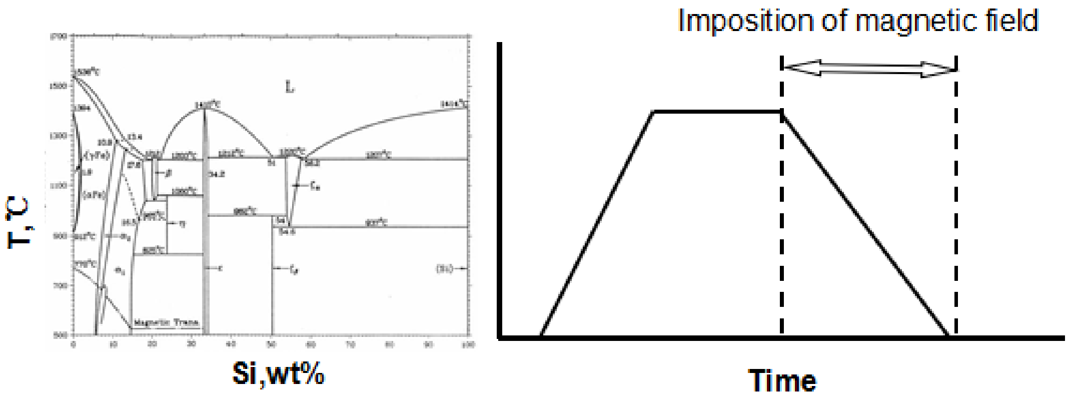

Fig.1: Phase diagram of the Fe-Si alloy (a); and temperature profiles for the solidification procedure(b)

3. Results

Fig.2 shows the microstructures of the Fe-1wt.%Si alloy solidified from 1540℃（melting state）at a cooling rate of 10K/min without and with a magnetic field, respectively. It can be observed that for the α ferrite phase in the Fe-1wt.%Si alloy, the effect of a high magnetic field on the growth of the α ferrite phase is weak. However, for the Fe-3wt.%Si alloy, an application of a high magnetic field has affected the dendrite growth significantly. Fig.3 shows the microstructures of the Fe-3wt.%Si alloy solidified from 1520℃（melting state）at a cooling rate of 10K/min without and with a magnetic field, respectively. In the case of no field, it can be observed that the structure of the alloy has a usual disordered nature; however, after the application of a 0.4T and 0.8T magnetic field, the needle-like α ferrite phases away from the wall of corundum crucible were break down to granular ferrite, needle-like α ferrite phase in the case of no magnetic field becomes the mixture of needle-like and granular-like α ferrite phase in the application of a 0.4T and 0.8T. As the magnetic field exceed 1T, the granular-like α ferrite phase disappear totally and needle-like α ferrite phase reappear and even coarsening. This means that the Si content in the alloy has played an important role during the morphology change of the α ferrrite phase.

4. Discussion

From the above experimental results, it can be learned that the magnetic field can affect the morphology of α ferrite phase. The effect of a high magnetic field on the growth of the needle-like α ferrite phase in the bulk solidified Fe-3wt.%Si has been investigated experimentally and it has been found that an application of a high magnetic field has caused the break and the coarsening of the α ferrite phase. Moreover, it is found that the Si content in the alloy has played an important role during the morphology change. This is attributed to the forces produced on the dendrite during the bulk solidification under a high magnetic field. Normally, there exist two force：the magnetic force(MF) and thermoelectric magnetic force(TEMF) during solidification under a high static magnetic field. The TEMF in liquid will drive some motions [i.e.so called thermoelectric magnetic convection (TEMC)]. The driving force varies as B and the braking force varies as B2, therefore, as shown by Shercliff [14],there is an optimum strength of the magnetic field. When the MFD is below the optimum strength, TEMF will break the needle-like α ferrite phase and result in the increase of the granular-like α ferrite phase ahead of the needle-like α ferrite phase. When the MFD exceed the optimum strength, Lorentz forces impede the flow of the melt, resulting the coarsening of needle-like α ferrite phase. As is well-known , the electromagnetic properties of Si-steel are improved by increasing Si content. So for different Si content alloys, the breaking behaviors of the α ferrite phase are different, owing to the

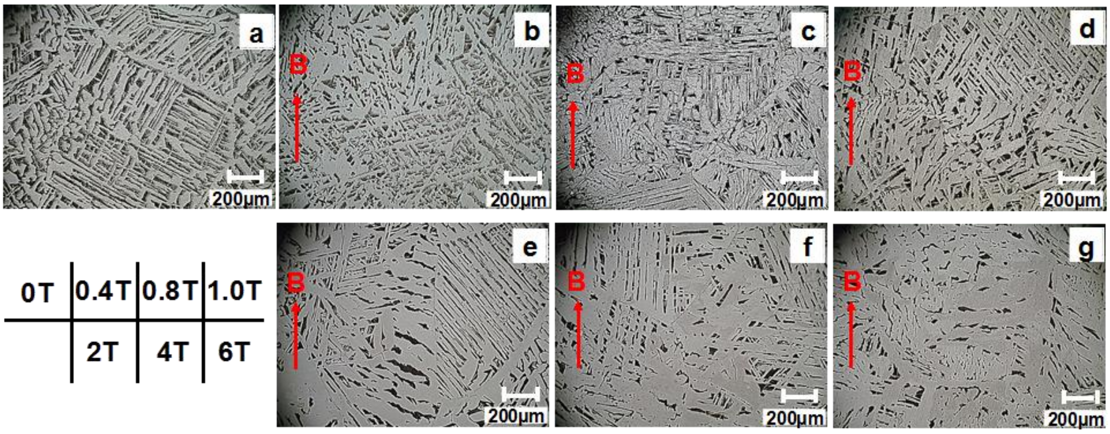

Fig.2:Microstructure of the Fe-1wt.%Si alloy solidified from melting state at a cooling rate of 10K/min:(a)0T;(b)0.4T;(c)0.8T;(d)1T;(e)2T;(f)4T;(g)6T.longitudinal microstructure

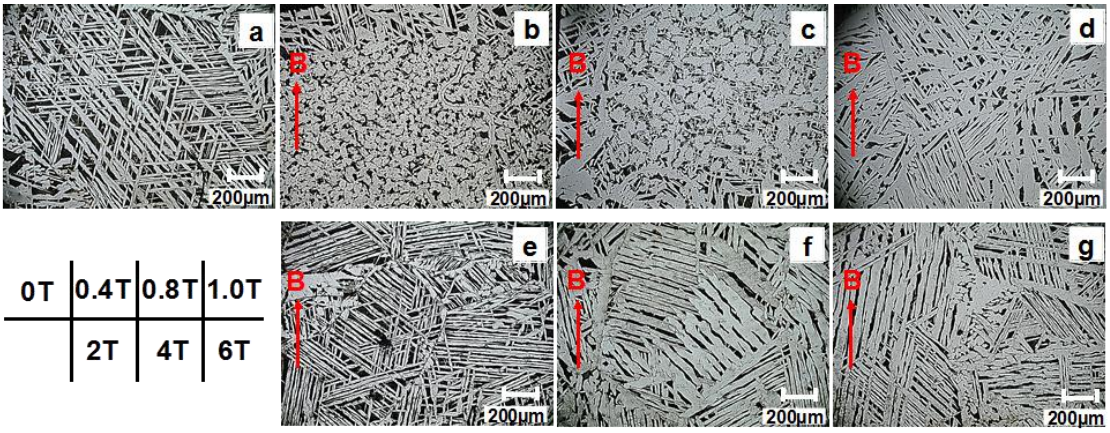

Fig.3: Microstructure of the Fe-3wt.%Si alloy solidified from melting state at a cooling rate of 10K/min:(a)0T;(b)0.4T;(c)0.8T;(d)1T;(e)2T;(f)4T;(g)6T.longitudinal microstructure

difference of the magnetic force of the dendrite. The above results have shown that an application of a high magnetic field has caused the occurrence of the breakdown of needle-like α ferrite phase not in Fe-1wt.%Si but in Fe-3wt.%Si. This may be attributed that the difference of magnetic force of Fe-Si alloy. Thus, under a certain MFD, the dendrites in the Fe-3wt.%Si alloy is easier to break down than the one in the Fe-1wt.%Si alloy. It should be emphasized that the above experimental results may act as an experimental proof that the force imposed on the dendrite during the bulk solidification will induce the occurrence of the strip morphology to the granular morphology.

4. Conclusions

Effects of a high magnetic field on the ferrite phase morphology transition in bulk solidified Fe-based alloys has been investigated experimentally. Results show that for different Si content in Fe-Si alloy, the effect of a high magnetic field on the growth of the α ferrite phase is different. Indeed, it has been found that the growth of the α ferrite phase in the Fe-1wt.%Si alloy becomes coarsening as the MFD increase. However, for the Fe-3wt.%Si alloy, a certain magnetic field has caused the occurrence of the needle-like to granular-like transitions of the α ferrite phase. This may be attributed to the thermoelectric magnetic force (TEMF) on the dendrite caused by the interaction between the thermoelectric current and the magnetic field. Above results may act as an experimental proof that the force imposed on the dendrite during the bulk solidification will induce the occurrence of the strip morphology to the granular morphology. Further, above results are discussed from the TEMF imposed on the dendrite and the different of the magnetic force of α ferrite phase in the different Si content.

Acknowledgements

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