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Effects of high magnetic field on modification of Al-Si alloy①

LIAN Feng(连 峰)[1, 2], QI Feng(齐 峰)[1],
LI Ting-ju(李廷举)[1], HU Guo-bing(胡国兵)[1]
(1. Materials Engineering College, Dalian University of Technology, Dalian 116024, China;
2. Electromechanics and Materials Engineering College, Dalian Maritime University, Dalian 116026, China)

Abstract: Effects of high magnetic field on modification of Al-6% Si hypoeutectic alloy, Al-12.6% Si eutectic alloy and Al-18% Si hypereutectic alloy were studied. For the Al-6% Si alloy, it is found that the sample modified by Na-salt does not lose efficacy after remelting under high magnetic field. For the Al-12.6% Si alloy, if the sample modified by Na-salt is kept at the temperature of modification reaction, high magnetic field can postpone the effective time of the modification. For Al-18% Si alloy modified by P-salt, the primary Si in solidified structure concentrates at the edge of the sample and eutectic Si appears in the center of the sample under the condition without high magnetic field, while the primary Si distributes evenly in the sample when the high magnetic field is imposed. It is thought that the high magnetic field restrains the convection of the melt.

Key words: high magnetic field; Al-Si alloy; modification
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1 INTRODUCTION

Among Al-Si alloys, the Al-Si eutectic alloy has the best foundry capability. The mechanical properties of Al-Si eutectic and hypoeutectic alloy highly relates to the shape, size and distribution of Si phase in eutectic structure. Coarse acicular-like eutectic Si dissevers Al matrix badly to induce stress concentration and debase the mechanical properties, especially the tenacity. Modification is the process to change the shape and size of eutectic Si, namely to change the shape of eutectic Si from coarse acicular-like to thin fibrous, and to improve the mechanical properties of Al-Si alloy[1-4]. Modification can be achieved by appending a few elements or cooling fast, of which the former is used more generally. The elements Na, Sr, Sb etc are usually utilized as the modificator, of which the element Na is most effective[5], but its effective time of modification is short. The modification efficiency declines generally after 30－60 min, and the effect of Na modification will disappear after remelting, therefore, it tends to be replaced by Sr, which is a little worse than Na. It is important to solve the two problems for Na modification. For the Al-Si hypereutectic alloy, modification is the process to refine primary Si through supplying foreign crystal nucleus to the melt. For example, modification can be achieved by appending P-salt. The aim of refining primary Si is realized while P is combined with Al and the high melting point compound AlP forms, which acts as foreign crystal nucleus. The Al-Si hypereutectic alloy modified has good cutting property if primary Si distributes evenly[6, 7]. Therefore, it is important to study the distribution of primary Si.

It was found that the modification effect was enhanced further and the dendrite size of α(Al) was refined by using rotary magnetic field[8]. SHI et al[9] studied the characteristics of the unidirectional solidification of Al-Cu alloy and the effects of 0.12 T magnetic field on the solidified structure. Hideyuki et al[10] studied the solidification of Cu with magnetic field and found that the convection of the suspended substances in Cu melt is difficult to control with 1 T magnetic field. With the development of superconductor, high magnetic field of about 10 T is available and can be used. Studies, such as improving material performance or developing new materials through controlling macro or microscopic processes of physicochemical reaction of materials with Lorenz and magnetic forces, become key research topics. For example, the solidified structure of Pb-15% Cu monotectic alloy wads block-like and segregation appeared in Pb-35.5% Cu hypermonotectic alloy under the condition without high magnetic field. However, the solidified structure of Pb-15% Cu alloy became fine and the segregation in Pb-35.55% Cu alloy was obviously improved with 10 T high magnetic field[11].

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Correspondence: LIAN Feng, PhD candidate; Tel: +86-411-84766535; E-mail: fengfeng0425@yahoo.com.cn

However, there are no studies on the effect of high magnetic field on the modification of Al-Si alloy.

In this research, the effects of high magnetic field on quality, remelting and effective time of Na-salt modification to Al-6% Si hypoeutectic alloy and Al-12.6% Si eutectic alloy are studied. The effects of high magnetic field on the distribution of primary Si in Al-18% Si hypereutectic alloy modified by P-salt are also studied.

2 EXPERIMENTAL

Al-6% Si, Al-12.6% Si and Al-18% Si (mass fraction, %) alloys were made from ZL102 (produced in Fushun) with pure Al or pure Si. The composition of ZL102 was as follows: Si 11.9%, Mn 0.01%, Cu 0.08%, Ti 0.02%, Fe 0.5%, Zn 0.005%, Mg 0.01% and balance Al.

The experimental apparatus is illustrated in Fig. 1. The inner diameter for generating high magnetic field is 100 mm and the height is 460 mm, the max magnetic flux density is 10.02 T. The diameter and height of the self-made heating furnace are 30 mm and 460 mm respectively. The furnace is heated by DC with the maximum power of 3 500 W, the temperature can reach higher than 1 000 ℃, and can be altered through adjusting the voltage. In the experiment, the heating furnace is put into the apparatus and the water-cooled tubes are placed between the inner wall of the apparatus and the furnace, the cooling water flows from bottom to top. The temperature is measured with K-type thermocouple.

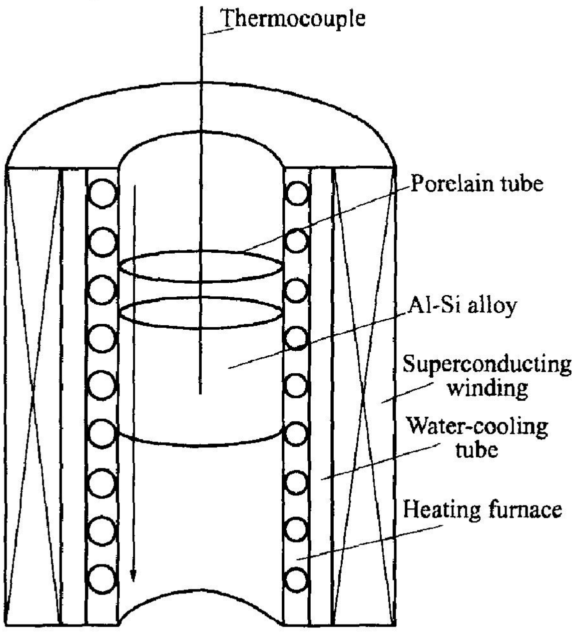

Fig. 1 Schematic diagram of experimental apparatus

Put the solid Al-Si alloy into a porcelain tube whose inner and outer diameters are 20 mm and 24 mm respectively, set the tube into a heating furnace, and then start to heat. For the Al-6% Si hypoeutectic alloy, at the temperature of modification reaction (720 ℃), add HGB-4 of about 2% of Al-6% Si alloy into the tube. The HGB-4 is composed of Cl-salt, K-salt, NaF etc, among which NaF accounts for 50%. When the temperature reduced to 520 ℃, two experiments were made: 1) Start-up of high magnetic field generator (it needs about 13 min for magnetic flux density to rise from 0 T to 10 T), and keep the temperature for 20 min. Then stop heating and cool the sample in the furnace. 2) Heat the sample again for remelting, start high magnetic field simultaneously. Keep the temperature of the sample at 720 ℃ for 20 min, and then stop heating and cool the sample in the furnace.

For the Al-12.6% Si eutectic alloy, at the temperature of modification reaction (760 ℃), add HGB-2 of 2% of Al-12.6% Si alloy into the tube. HGB-2 is mainly composed of Cl-salt and NaF, of which NaF shares 60%. After the modification reaction, start high magnetic field, keep the temperature of 760 ℃ for 20 min and 40 min respectively, and then stop heating and cool the sample in the furnace.

For Al-18% Si hypereutectic alloy, at the temperature of modification reaction (780 ℃), add P-salt compound of 1.5% of Al-18% Si alloy into the tube. After the modification reaction, start high magnetic field, keep the temperature of 780 ℃ for 20 min and 40 min respectively, and then stop heating and cool the sample in the furnace.

The cooling speed in all experiments is 20 ℃/min. Stop high magnetic field after the sample is cooled to the room temperature. Repeat the above experiments without imposing high magnetic field. Cut samples at 20 mm from bottom, grind and polish the section and then corrode the section with 0.5% HF. Observe the solidified structure of the cross and vertical sections with optical microscope and take pictures of them.

3 RESULTS

3.1 Al-6% Si hypoeutectic alloy

Fig. 2 shows the solidified structure of the sample that was kept at the temperature of 520 ℃ for 20 min. It is indicated that eutectic Si becomes fine fibriform and the modification is good under the conditions with or without high magnetic field at 520 ℃. High magnetic field does not influence the modification effect after the modified sample is solidified.

Fig. 3 shows the solidified structure of the remelted sample that was kept at 720 ℃ for 20 min. It is indicated from Fig. 3 that the eutectic Si is coarse plate-like or acicular, and the distribution

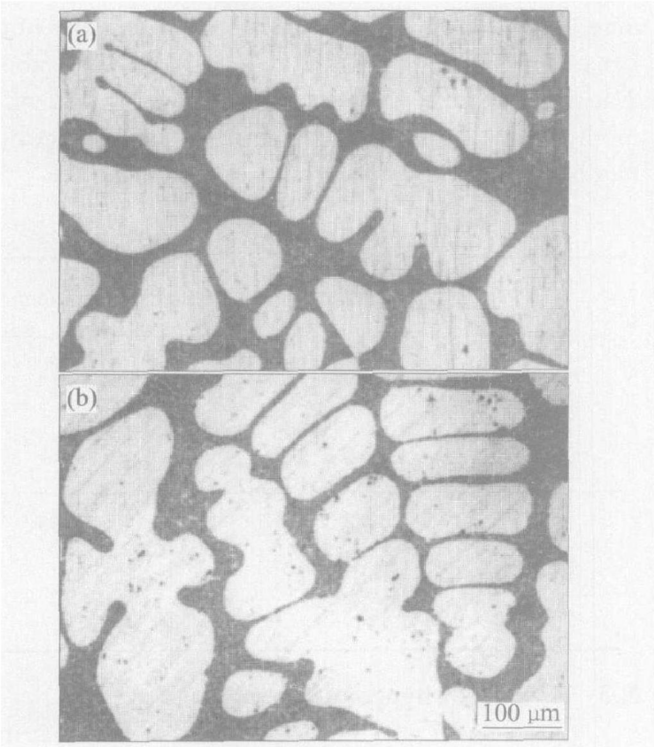

Fig. 2 Solidified structures of Al-6% Si alloys (520 ℃, 20 min)
(a) —Without high magnetic field;
(b) —With high magnetic field

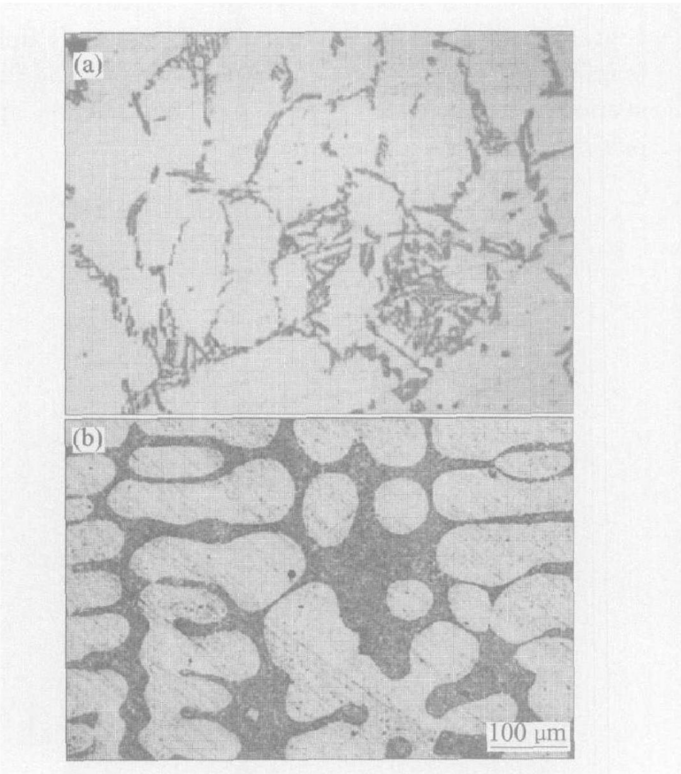

Fig. 3 Solidified structures of Al-6% Si alloys (720 ℃, 20 min)
(a) —Without high magnetic field;
(b) —With high magnetic field

and length of Si are uneven under the condition without high magnetic field. While under the condition with high magnetic field, eutectic Si becomes fine fibriform and distributes evenly. Alpha Al becomes round and blunt. When the modified sample was remelted, modification lost efficacy under the condition without high magnetic field but still had efficacy under the condition with high magnetic field.

3.2 Al-12.6%Si eutectic alloy

The solidified structure of the sample that was kept at 760 ℃ for 20 min is shown in Fig. 4. From Fig. 4 it can be seen that eutectic Si becomes fine and even, and more granular Si are generated under the condition with high magnetic field. The modification with high magnetic field is obviously better than that without high magnetic field. Therefore, after the Na-salt modified sample was kept at the temperature of modifying reaction for 20 min under the condition without high magnetic field, the modification quality declined badly. The sample is similar to the sample of bad modification. But the modification efficacy still remains under the condition with high magnetic field.

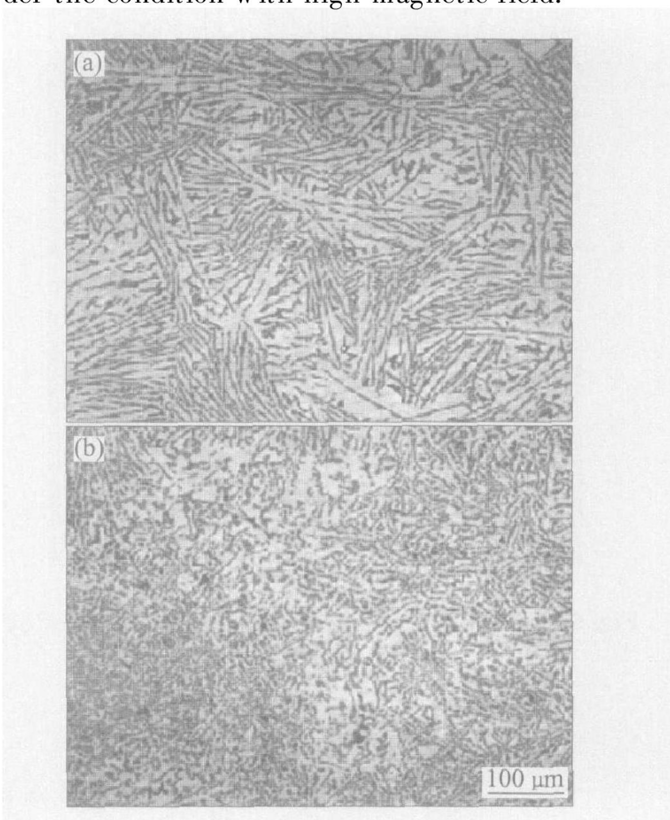

Fig. 4 Solidified structure of Al-12.6% Si alloys kept for 20 min at 760 ℃
(a) —Without high magnetic field;
(b) —With high magnetic field

Fig. 5 shows the solidified structures of the sample that was kept at 760 ℃ for 40 min. It is indicated that in the case without high magnetic field the eutectic Si becomes rough obviously, most eutectic Si is coarse plate-like or acicular, and the space between eutectic Si becomes larger than that kept for 20 min. The modification efficacy almost disappears. However, under the condition with high magnetic field, although eutectic Si is still longer than that kept for 20 min, eutectic Si is denser and the shape is contorted, whose length is shorter than that without high magnetic field. That is to say, after keeping the temperature for 40 min the efficacy of modification without high magnetic field declines greatly. While under the condition with high magnetic field, although the decline still happens, the modification efficacy is kept in some degree. Moreover under the condition with high magnetic field, the modification efficacy after keeping for 40 min is better than that after keeping for 20 min without high magnetic field.

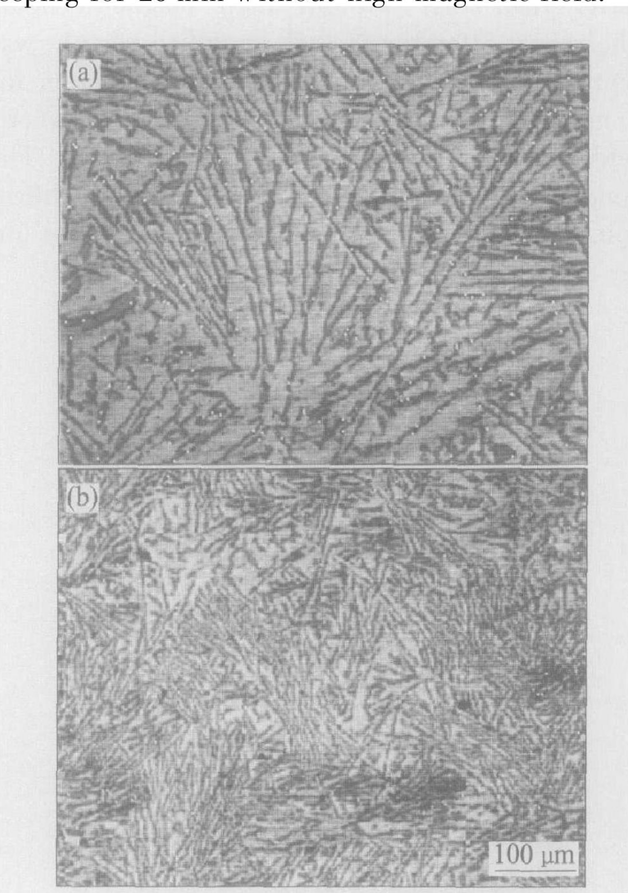

Fig. 5 Solidified structures of Al-12.6%Si alloys (760 ℃, 40 min)
(a) —Without high magnetic field;
(b) —With high magnetic field

The changes of eutectic Si were analyzed by the method of counting the number of eutectic Si with a square of 10 mm × 10 mm in photos, and the results are shown in Table 1. It is shown that when keeping the temperature for 20 min, the average number of eutectic Si on cross and vertical sections is 24 under the condition without high magnetic field, while the number is 47.5 under the condition with high magnetic field. When keeping the temperature for 40 min, the average number of eutectic Si on cross and vertical sections is 14 under the condition without high magnetic field and is 34 under the condition with high magnetic field respectively. The number of eutectic Si with high magnetic field is about 2 times of that without high magnetic field when modified for 20 min; the number of eutectic Si with high magnetic field is about 2.5 times of that without high magnetic field when modified for 40 min. It is proved that eutectic Si has been fined greatly by high magnetic field.

Table 1 Statistic result of eutectic Si

Holding time/min	High magnetic field	Section	Number
20 min	Without	Cross	23
		Vertical	25
	With	Cross	48
		Vertical	47
40 min	Without	Cross	16
		Vertical	23
	With	Cross	33
		Vertical	35

3.3 Al-18%Si hypereutectic alloy

Fig. 6 and Fig. 7 show the solidified structures of the sample that was kept at 780 ℃ for 40 min. From Fig. 6 and Fig. 7 it can be seen that under the condition without high magnetic field, primary Si in solidified structure concentrates at the edge of the sample and eutectic structure appears in the center of the sample. After the high magnetic field is imposed, primary Si distributes evenly in the full section of the sample. The same phenomenon appears while the keeping time is 20 min.

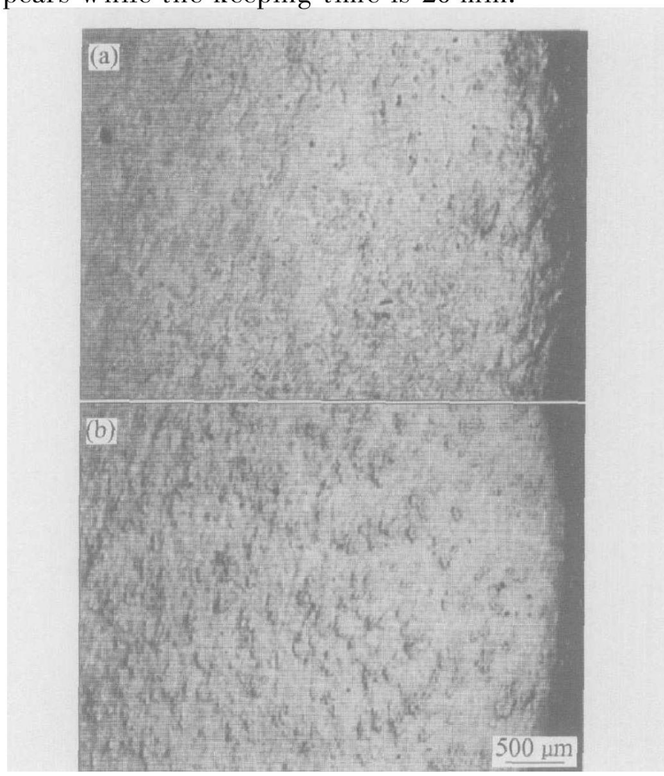

Fig. 6 Solidified structures of Al-18%Si alloys kept at 780 ℃ for 40 min
(a) —Without high magnetic field;
(b) —With high magnetic field

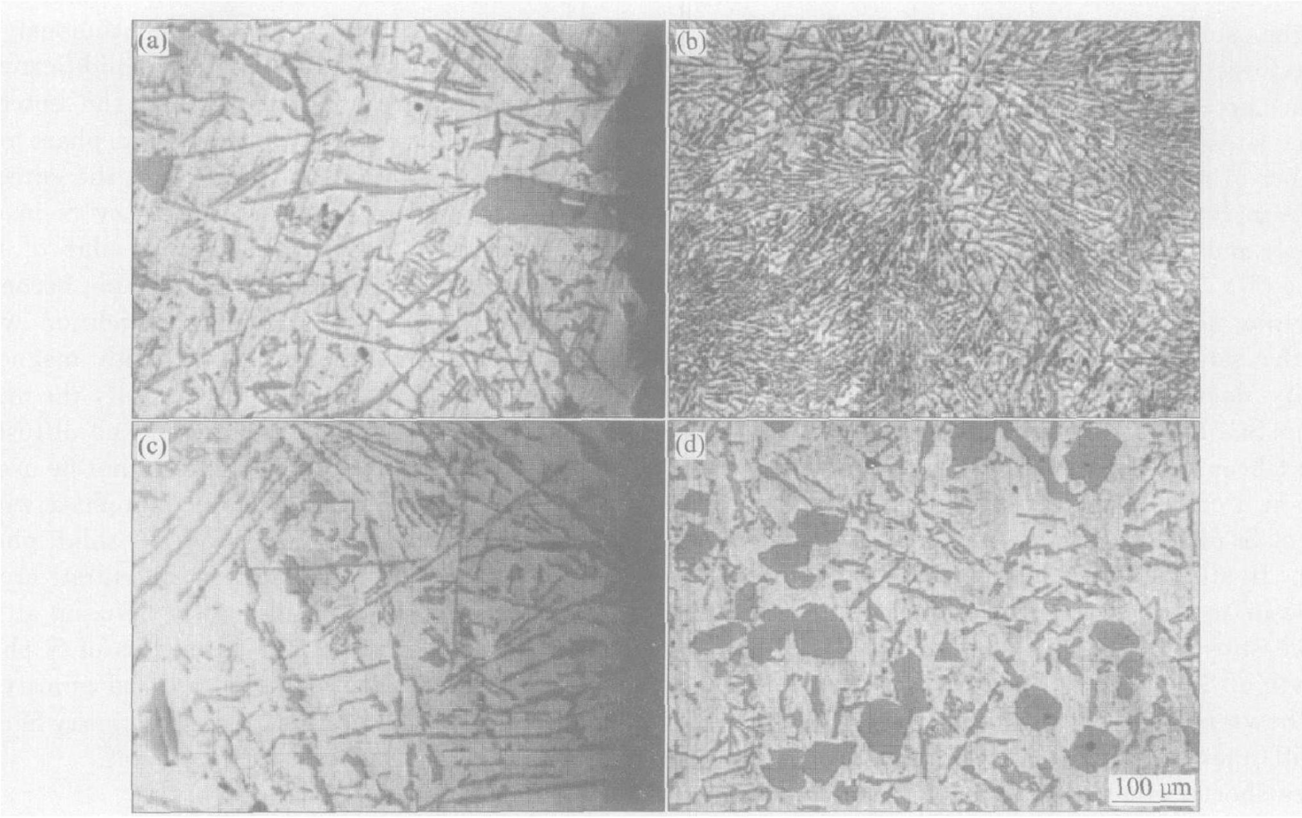

Fig. 7 Solidified structures of Al-18% Si alloys kept at 780 ℃ for 40 min
(a) —Edge of sample without high magnetic field; (b) —Center of sample without high magnetic field;
(c) —Edge of sample with high magnetic field; (d) —Center of sample with high magnetic field

4 DISCUSSION

According to the "poisoning" mechanism[12], after Na-salt is added, Na is adsorbed on the solid/liquid interface of Si phase, the connatural growth stage is poisoned to make the growth on the side of connatural stage lose its advantage. As a result, dynamic undercooking augments so great that twin occurs continually. When warmed at the temperature of the modification reaction, the acting of convection may intensify the diffusion of Na atoms on the solid/liquid growth front. Therefore, the concentration of Na atoms on solid/liquid growth front decreases. Decreasing the occupying probability of Na atoms on twin surface crystal lattice site may make it difficult for Si growth to become twin growth. Si still appears with the shape of coarse acicular-like. It can be seen from Fig. 3(a) that remelting loses its efficiency. It can be seen from Fig. 4(a) that the modification quality declines obviously. Meantime, since Na is an active factor, it can be oxidized and burned seriously, the modification quality disappears completely after held for 40 min and the coarse acicular-like eutectic Si is obtained as shown in Fig. 5(a).

As shown in Fig. 8 under the condition with high magnetic field, the inductive electric current J_z is produced when liquid flows in the direction with v_x that is not parallel to the direction of high magnetic field B_y. The lorentz force $F_x = J_z \times B_y = (\sigma v_x \times B_y) \times B_y$ is produced by the interaction between the inductive electric current and the high magnetic field. Here, σ is the conductivity and v_x is the flow velocity of liquid. The direction of Lorentz force F_x opposes to the direction of liquid flow v_x. Then the flow of liquid is controlled by Lorentz force. This means that high magnetic field can restrain flows in all directions except B direction[13].

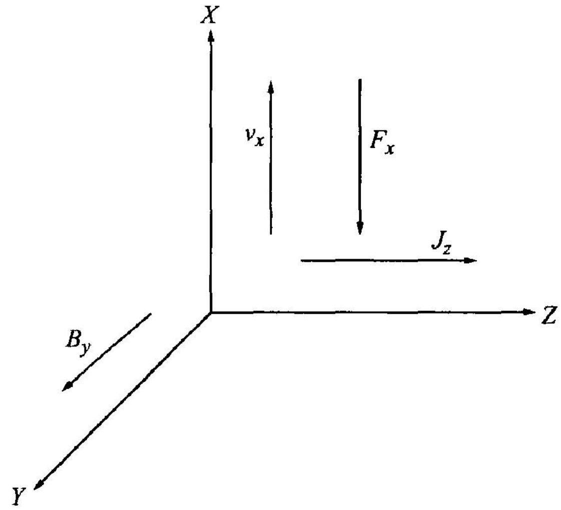

Fig. 8 Principle of control of high magnet field on convection

Due to the impact of magnetic field on convection, it is difficult for Na atoms, which concentrate on the solid/liquid growth front, to diffuse. Therefore, it can control the growth of Si phase surface greatly. Na atoms may occupy more crystal lattice sites of twin crystal surface to increase the number of twin. If the Na quantity is enough, due to the increment of the twin, the Si crystals ramify densely and form a ball shape structure as shown in Fig. 4(b). This means that with magnetic field remelting does not lose Na modification efficiency for the sample of Al-6% Si, while modification quality does not decline for the sample of Al-12.6%Si. Even kept for 40 min, the Na that hasn't been oxidized and burned can still concentrate at a certain density on the solid/liquid interface of Si phase due to the impact of the magnetic filed. It still limits the growth of surface of Si phase in some degree, and occupies some crystal lattice sites of twin crystal surface to make the growth of Si change to the growth of twin crystal. As shown in Fig. 5(b), in this situation eutectic Si is still fine, with twist shape, and its length becomes shorter compared with the situation without magnetic filed.

Moreover based on the analysis of Zigzag twin growth model, the mechanism of Na modification is that Na is adsorbed on the {111} surface of Si crystal and decreases the boundary energy of twin crystal, and results in the increment of the density of twin crystal[14]. In the case of warming at the temperature of reaction of modification, due to the impact of convection only a few Na atoms can be adsorbed on the {111} surface of Si crystal, then it does not against decrease the boundary energy of twin crystal. Since magnetic field limits the convection of melt, more Na atoms may be adsorbed on the {111} surface of Si crystal to increase the density of twin crystal further. Thus Si phase in eutectic structure, which is obtained through warming with magnetic field, becomes finer, and the efficiency of modification is better.

When kept at temperature of 520 ℃, Al-6%Si alloy has solidified at the temperature and there is no convection. The modification efficiency remains. Therefore, the modification efficiency does not lose if the modification temperature is kept below the frozen point. Meantime, since the action of magnetic field on convection does not work, the efficiency of magnetic field on modification can not be found when warmed at 520 ℃ as shown in Fig. 2(a) and Fig. 2(b).

For Al-18% Si hypereutectic alloy, under the condition without high magnetic field, the analysis model of full diffusion of liquid phase due to the convention and no diffusion of solid phase during solidification is used[15]. Primary Si appears at the edge of first solidification. Si atom diffuses from liquid phase to solid phase at the front of the solidification. Then primary Si appears continuously at the edge of the sample along with solidification. When the temperature decreases to the eutectic temperature, the composition of liquid phase reaches the composition of eutectic, then the eutectic structure generates. Therefore, primary Si in solidified structure concentrates at the edge of the sample and the central part of the sample becomes the eutectic structure. Under the condition with high magnetic field, because the high magnetic field restrains the convection of the melt, the model of full diffusion of liquid phase and no diffusion of solid phase during solidification can not be used. The model of limited diffusion of liquid phase without convection and no diffusion of solid phase should be used. Si atom can not concentrate at the edge of the sample due to its limited diffusion at the front of the solidification. Crystal nucleus of Si phase is produced in the whole liquid phase and primary Si appears in the liquid everywhere. Then primary Si distributes evenly in all sections of the sample.

5 CONCLUSIONS

1) Remelting does not lose the efficiency of Na-salt modification for the Al-6% Si hypoeutectic alloy under the condition with high magnetic field.

2) High magnetic field has no effect on the modification efficiency of the Al-6% Si hypoeutectic alloy when temperature is below frozen point.

3) When Na-salt modified Al-12.6% Si eutectic alloy is kept at the temperature of modifying reaction for 20 min under the condition with high magnetic field, eutectic Si becomes fine and the modification efficiency is better than that under the condition without high magnetic field.

4) When the holding time extends to 40 min under the condition with high magnetic field, the modification efficiency still partly remains. In other words, high magnetic field can postpone the effective time of the modification.

5) If the sample of the Al-18% Si hypereutectic alloy modified by P-salt is kept at the temperature of modification reaction for 20 and 40 min under the condition without high magnetic field, primary Si in solidified structure concentrates at the edge of the sample and eutectic structure appears in the center of the sample. While the high magnetic field is imposed, primary Si distributes evenly in the whole section of the sample. It is thought that the high magnetic field restrains the convection of the melt.

REFERENCES

[1] ZHAO Ai-min, MAO Wei-min, ZHEN Zi-sheng, et al. Effects of cooling rate on solidification microstruc-

tures and wear resietance of hypereutectic Al-Si alloy [J]. The Chinese Journal of Nonferrous Metals, 2001, 11(5): 827 - 833. (in Chinese)

[2] LIAO Heng-cheng, XIA Jin-hong, SUN Guo-xiong. Influence of combined melt treatment of Sr+ B on microstructure and mechanical properties of Al-Si-Mg casting alloy [J]. The Chinese Journal of Nonferrous Metals, 2003, 13(1): 27 - 34. (in Chinese)

[3] LIAO Heng-cheng, DING Yi, SUN Guo-xiong. Effect of strontium on columnar growth of dendritic α phase in near-eutectic Al-11.6%Si alloy [J]. Trans Nonferrous Met Soc China, 2004, 14(4): 728 - 732.

[4] Shamsuzzoha M, Hogan L M, Berry J T. Effects of modifying agents on crystallography and growth of silicon phase in Al-Si casting alloys [J]. AFS Trans, 1993, 101: 999 - 1005. (in Chinese)

[5] ZHOU Yong-xin, LU Zhen-lin, ZHAO Xi-cheng. The alternative of research and development of Al-Si alloy [J]. Foundry Technology, 2004, 25(1): 13 - 14. (in Chinese)

[6] ZHANG Jin-shan, XU Chun-xiang, HAN Fu-yin. Effect of composite modifier on structures and properties of hypereutectic Al-Si alloy [J]. The Chinese Journal of Nonferrous Metals, 2002, 12(S1): 107 - 110. (in Chinese)

[7] QUAN Yan-ming, ZHOU Ze-hua, ZHANG Fa-ying. Effect of structure of hypereutectic Al-Si alloy on machinability [J]. Chinese Journal of Mechanical Engineering, 1998, 34(1): 1 - 6. (in Chinese)

[8] LI Gao-hong, LI Jian-ping, XIA Feng, et al. Effect of combination modification and electromagnetic stir refining on structure of hypereutectic Al-Si alloy [J]. Hot Working Technology, 2004(6): 9 - 11. (in Chinese)

[9] SHI Hai-fang, GU Chun-lei, LIU Qing. Effects of DC magnetic field on directionally solidified Al-Cu alloy [J]. Nonferrous Metals, 2003, 55(1): 13 - 17. (in Chinese)

[10] Yasuda H, Ohnaka I, Ninomiya Y, et al. Levitation of metallic melt by using the simultaneous imposition of the alternating and the high magnetic fields [J]. Journal of Crystal Growth, 2004, 260(3): 475 - 485.

[11] JIN Jun-ze, LI Ting-ju. New advance in electromagnetic processing of materials[J]. Rare Metal Materials And Engineering, 2000, 29(S1): 79 - 83. (in Chinese)

[12] Lu S Z, Hellawell A. Growth mechanisms of silicon in Al-Si alloys [J]. J Crystal Growth, 1985(73): 316 - 328.

[13] Asai S. Electromagnetic Processing of Materials [M]. Uchid A Rokakuho Publishing Co, Ltd, 2000.

[14] Shamsuzzoha M, Hogan L M. The crystal morphology of fibrous silicon in strontium-modified Al-Si eutectic [J]. Philosophical Magazine A, 1986, 54(4): 459 - 477.

[15] GUAN Yu-long, TU Bao-hong. Solidification Process [M]. Beijing: Metallurgical Industry Press, 1981.

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