Article ID: 1003 - 6326(2004)05 - 0846 - 05

Microstructure of electromagnetic stirred semi-solid AZ91D alloy①

MAO Wei-min(毛卫民), ZHEN Zi-sheng(甄子胜), CHEN Hong-tao(陈洪涛), ZHONG Xue-you(钟雪友)
(School of Materials Science and Engineering,
University of Science and Technology Beijing, Beijing 100083, China)

Abstract: The microstructures of semi-solid AZ91D alloy stirred by rotationally electromagnetic field were studied. The shape of primary α-Mg phase is dendrite under conventional solidification condition and the primary α-Mg grains are changed to the fine rosette-like or granular grains under electromagnetic stirring condition. If the electromagnetic stirring frequencies are low, there are a large amount of fine rosette-like primary α-Mg grains and the fine rosette-like primary α-Mg grain in two dimensions belongs to a single grain in three dimensions; there are also many spherical primary α-Mg grains, they may belong to a single grain in three dimensions and the orientation differences of the grains between them are very small. If the electromagnetic stirring frequencies are high, a lot of the fine rosette-like primary α-Mg grains disappear and are converted into granular grains, and moreover, most of these granular grains belong to different grains in three dimensions.

Key words: semi-solid; magnesium alloy; electro-magnetic stirring; microstructure
CLC number: TG 146.2 **Document code:** A

1 INTRODUCTION

The densities of magnesium alloys are the smallest in engineering metallic materials, generally 1.75 - 1.85 g/cm^3 and properly 64% of aluminum alloys or 23% of steels. Their specific strength and fatigue strength, however, are higher than those of aluminum alloys[1]. Therefore, the mass of the structural parts made from magnesium alloys decreases obviously and these alloys have been used in the aeronautic and astronautic industries on a large scale. With the development of car' mass decrease in the recent years, it is urgently required to further reduce the mass of cars' structural parts, which can lower fuel exhaustion and environmental pollution. In order to satisfy the demand of decreasing the cars mass, the cars industry has put its eyes on the magnesium alloys and has promoted the basic research and applied development of magnesium alloys. The thixomolding and the New Rheocasting technologies are two of the above-mentioned research results, which are the advanced forming technologies of magnesium alloys after the semi-solid forming technology has been applied to many kinds of aluminum alloys[2-8]. However, there are also many basic and technological problems that need to be solved nowadays for developing more advanced and economical semi-solid forming technology of magnesium alloys. The mechanism of the microstructural transformation of magnesium alloys under different field conditions is one of the most basic study contents. Kamado et al[9] studied the effect of mechanical stirring on the microstructure of semi-solid AZ91D magnesium alloy and found that it was favorable for the spherical process of primary α-Mg grains when the stirring rate increased and the stirring time prolonged. Hao et al[10] studied the microstructures variation of AZ91D magnesium alloy kept isothermally in the semi-solid region, and found that the primary α-Mg grains were gradually changed to spherical shape at 570 ℃ with the time increasing and evenly suspended in the liquid, and moreover, the spherical process was faster and the primary α-Mg grains were some smaller in size when AZ91D magnesium alloy was modified before isothermally holding. LE et al[11] investigated the microstructure evolution of AZ91D during partially remelting processing. ZHEN et al[12] have roughly investigated the effect of electromagnetic stirring process parameters on the microstructure of semi-solid AZ91D alloy. However, the microstructural evolution of magnesium alloys stirred by differentially rotational electromagnetic field has not been very much clear yet. So this paper studies the microstructural characteristics of AZ91D magnesium alloy stirred by rotational electromagnetic field, which makes the basically applied technologies of semi-solid magnesium alloys more abundant and provides a

① **Foundation item:** Project(G2000067202) supported by the National Basic Research Program of China; project(G2002AA336080) supported by the Hi-tech Research and Development Program of China; project(50374012) supported by the National Natural Science Foundation of China
Received date: 2004 - 01 - 05; **Accepted date:** 2004 - 06 - 07
Correspondence: MAO Wei-min, Professor, PhD; Tel: + 86-10-62332882; Fax: + 86-10-82952879; E-mail: weiminmao@263.net

promise for the further development of the semi-solid forming process of magnesium alloys.

2 EXPERIMENTAL

The experimental metallic material was commercial billet of AZ91D magnesium alloy and its compositions are shown in Table 1.

Table 1 Composition of AZ91D alloy used in this study (mass fraction, %)

Al	Zn	Mn	Be	Si
8.92	0.617	0.208 4	0.001 1	0.023

Fe	Cu	Ni	Mg
0.002 3	0.001 4	0.000 8	Bal.

All experiments were conducted on the self-made electromagnetic stirring equipment, which was described in detail in Ref. [13]. The billet of AZ91D magnesium alloy was first machined to d55 mm × 55 mm and then put into a graphite crucible and sheathed with a threaded graphite lid. The graphite crucible was then placed into the stirring chamber and covered with the furnace lid. When all ready, the furnace was switched on, then the alloy was heated. When the AZ91D magnesium alloy was heated up to a given temperature above the liquidus one, the melt began to be continuously cooled down and stirred simultaneously by rotational electromagnetic field. The stirring process was maintained until the AZ91D magnesium alloy melt was cooled down to the given temperature in the semi-solid region, and the AZ91D billet including the crucible was thrown into water in order to avoid any structure evolution during the following cooling process.

The metallographic specimens were cut from the given positions of the stirred billets and were roughly ground, finely polished and etched. The microstructural characteristics in two dimensions were observed and analyzed with optical microscope. The microstructural characteristics in three dimensions were analyzed through sectional metallography and EBSD (electron back scatter diffraction) methods.

3 RESULTS AND DISCUSSION

3.1 Basic microstructural characteristics

Fig. 1 illustrates the microstructures of AZ91D magnesium alloy solidified under different conditions. Fig. 1(a) is the microstructure of the as-cast billet solidified on conventional condition and the microstructure mainly consists of primary α-Mg grains and intermetalic compounds of Mg_{17}-Al_{12} (β phase) and AlMn, which are stretched in the grain boundaries. The primary α-Mg grains are typical dendrites that have six secondary arms symmetrically having an angle of 60° to each other on the first stem. Fig. 1(b) is the as-cast microstructure of the alloy melt solidified at slow cooling

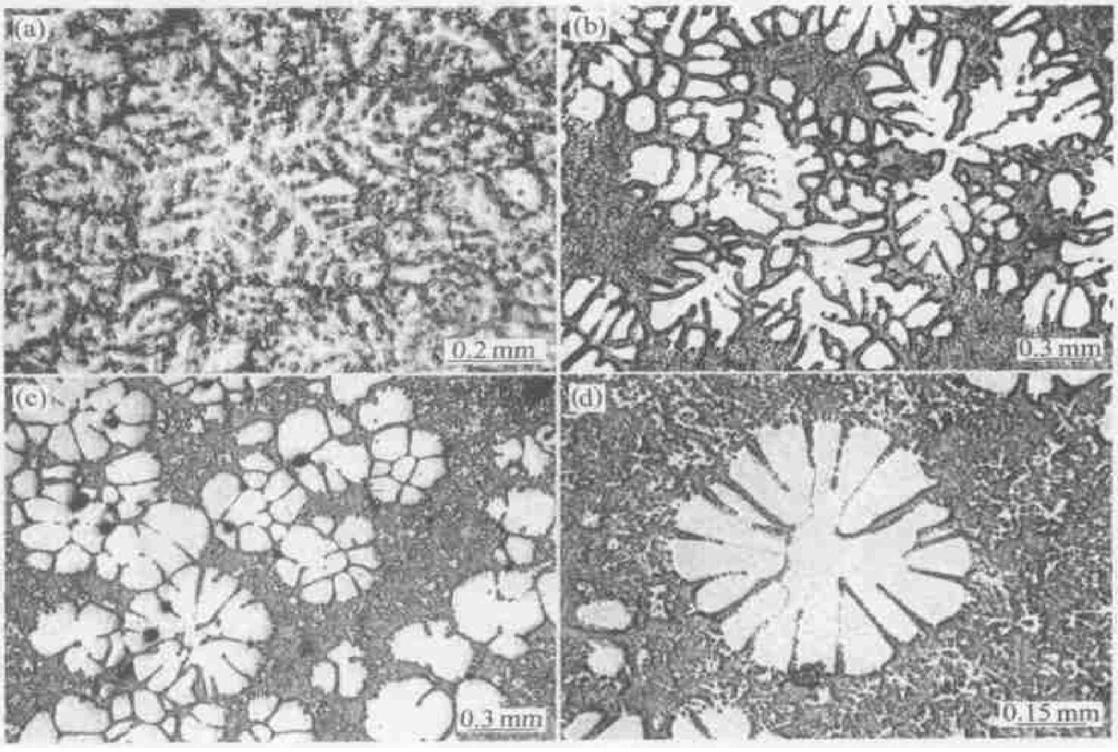

Fig. 1 Microstructures of AZ91D alloy solidified under different conditions
(a) —Conventional condition; (b) —At slow cooling rate;
(c), (d) —Stirred at 100 Hz, 100 V and 50 Hz, 60 V, respectively and quenched in water at 585 ℃

rate and quenched in water at 580 ℃ and the microstructure is similar to that in Fig. 1(a). The primary α-Mg grains in Figs. 1(a) and (b) always exhibit dendrites with six branches because they have close-packed hexagonal crystal lattice. Figs. 1(c) and (d) are the as-cast microstructure of the alloy melt solidified under electromagnetic stirring condition and quenched in water at 585 ℃. The morphology of the primary α-Mg grains in Fig. 1(c) appears in the fine rosette-like and spherical shape. Fig. 1(d) is the magnified photograph from Fig. 1(c) and the secondary arms of primary α-Mg grain are almost arranged in divergent direction.

3.2 Three-dimensional analysis of microstructures

The microstructural information in the two-dimensional section can only be obtained through traditional metallographic technology and the observed results may often have one-sidedness for microstructural analysis so that it is easy to lead to misinterpretation. In this work, the three-dimensional microstructures of AZ91D magnesium alloy samples are analyzed through two ways.

There are usually rosette-like and spherical grains in 2D section in the microstructures of the sample stirred by electromagnetic field. The rosette-like grain should be a single grain and the spherical grains appear to belong to each single grain respectively in general. But is it the real fact in 3D? The morphology of the rosette-like grains and appearing spherical grains in three dimensions has been detected through a sectional metallographic method, as shown in Fig. 2. The real space distance between any two adjacent metallographic planes in one sample is given below the corresponding metallographs. Figs. 2(a) and (b) are the detected results of different metallographic regions respectively. Analyzed from Fig. 2(a), the rosette-like grains also show rosette-like shape in the first photographs of the two-dimensional section, but the rosette-like grains gradually disappear and become several spherical grains in the two-dimensional section. This means that the many appearing spherical grains in 2D section may belong to one single grain in 3D. The largest size of the single rosette-like α-Mg grain in Fig. 2(a) is about 600 μm and the thickness polished away in perpendicular direction is about 347 μm, which is the half of the grain size in the perpendicular direction, and so the real size in the perpendicular direction is about 700 μm. Analyzed from Fig. 2(b) in the same way, the same results can be obtained and the largest size of the single primary α-Mg grain in the sectional figures is about 300 μm and the size in the perpendicular direction is about 700 μm. It is also found that the size difference of the rosette-like α-Mg grain between the preceding three sectional figures is very small. As a result, the morphology of the rosette-like α-Mg grains of AZ91D magnesium alloy stirred by electromagnetic field may be rod-like or ellipsoid-like in the three-dimensional space.

Fig. 3(a) is the conventional microstructure in two dimensions and Fig. 3(b) is the crystal orientational figure corresponding to Fig. 3(a) detected by EBSD method. The grains with the near color or the same color show that the grains' crystal orientation is the same or near each other and the grains with the obviously different color show that the grains' crystal orientation difference is large. These grains with the near color or the same color

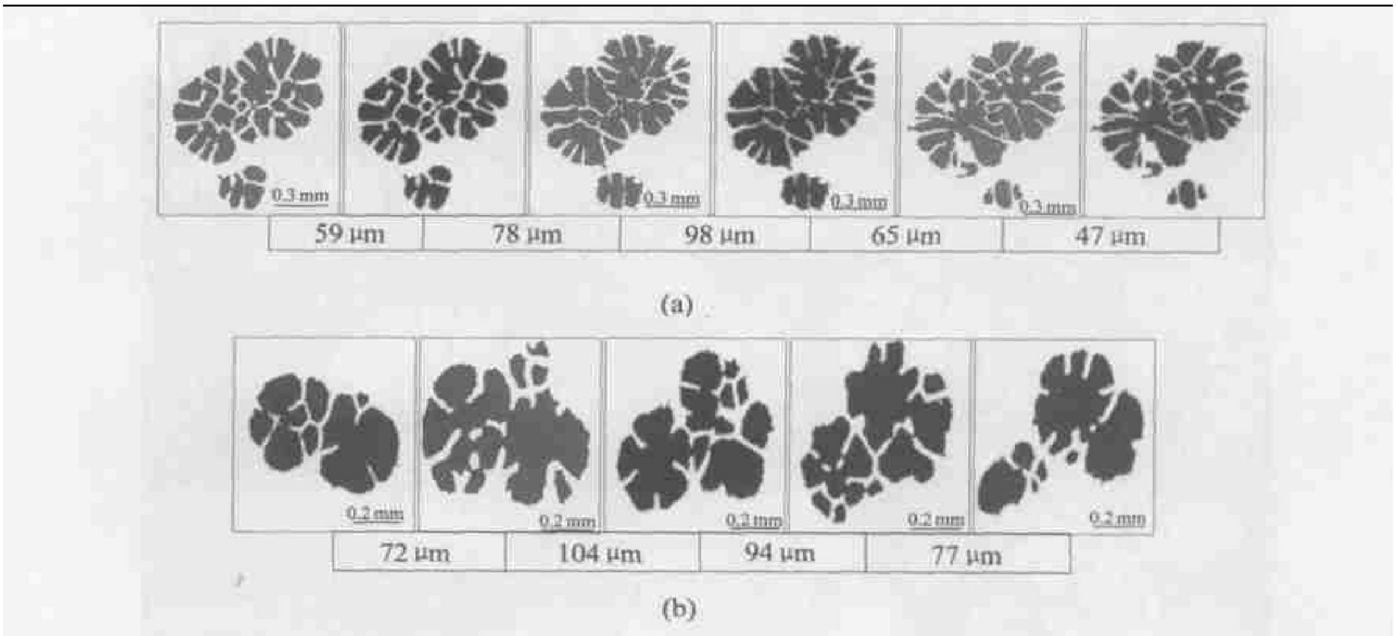

Fig. 2 Different sectional microstructures of AZ91D alloy stirred by electromagnetic filed
((a) and (b) are different metallographic region, respectively)

should belong to a single grain in three dimensions from the analyzed results of Fig. 2. These grains with the obviously different color should belong to a different grain in three dimensions. Therefore, it can be known from Fig. 3 that a rosette-like grain as well as all the little granular primary α-Mg grains included in the inside of the rosette grain come from one single crystal and all the little granular grains belong to different branches. The above conclusion is very similar to the conclusions from Refs. [13, 14].

3.3 Effect of electromagnetic stirring process on morphology

Fig. 4 shows the microstructure of AZ91D magnesium alloy stirred at different electromagnetic frequencies and the corresponding EBSD polar figures. It can be seen from Fig. 4 that the semi-solid microstructures of AZ91D magnesium alloy have obvious difference solidified under different stirring conditions. If the stirring power is not changed, the higher the electromagnetic stirring frequency is, the smaller the size of the primary α-Mg grains is and the most rosette-like primary α-Mg grains are converted into separated spherical grains in 2D section. In order to decide whether these separated spherical grains belong to one single grain, the microstructures of semi-solid AZ91D magnesium alloy are analyzed by EBSD method. The results show that under the higher electromagnetic frequency and especially at 200 Hz, the separated spherical primary α-Mg grains do not be-

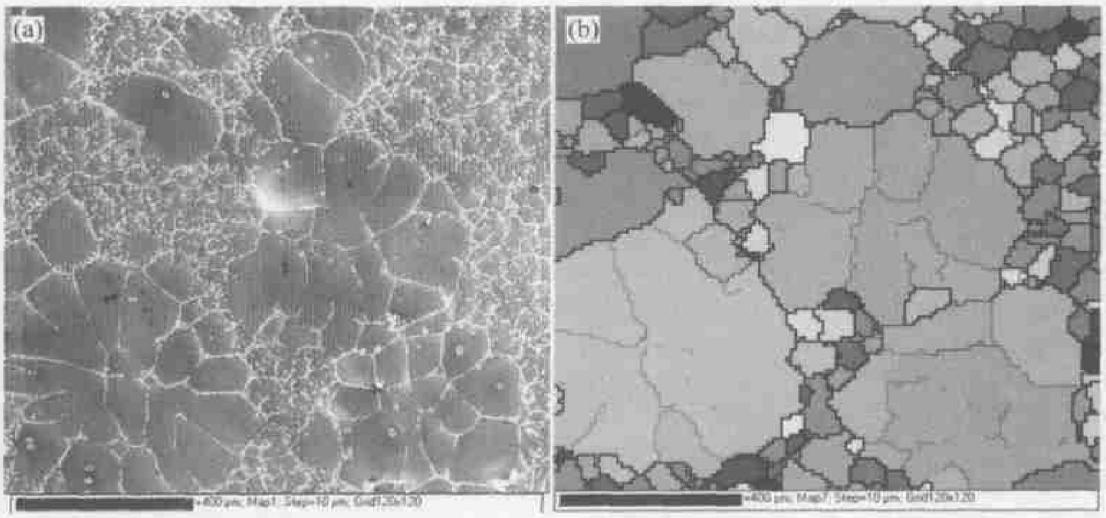

Fig. 3 Microstructure of AZ91D alloy stirred by electromagnetic filed(a) and corresponding EBSD crystal orientational figure(b)
(a)—Conventional microstructure in two-dimensional plane; (b)—EBSD crystal orientational figure

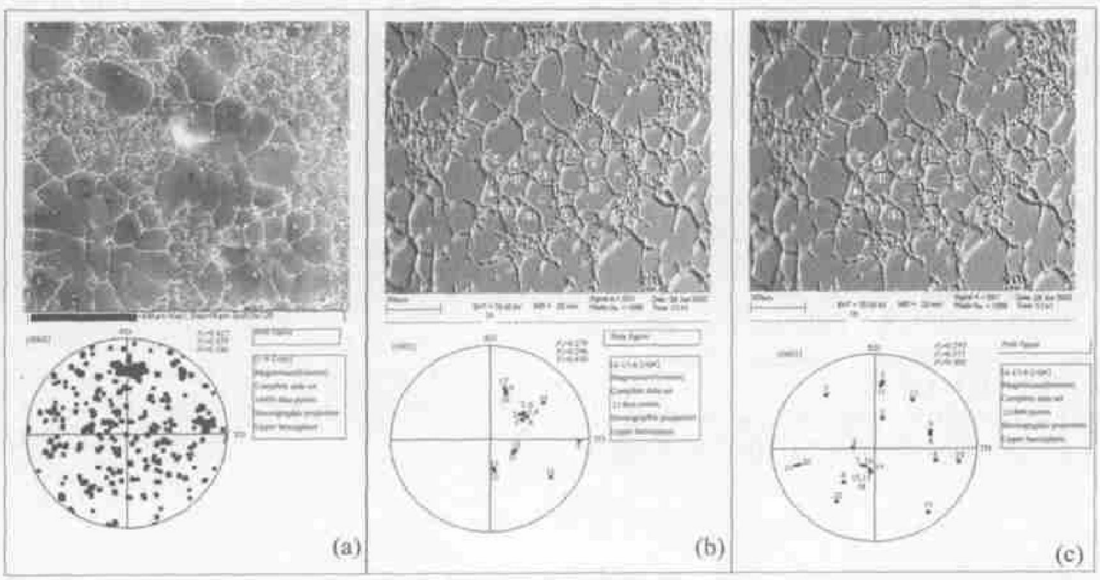

Fig. 4 Microstructures of AZ91D alloy stirred at different electromagnetic frequency and corresponding EBSD polar figures
(a)—50 Hz, 1.5 kW; (b)—100 Hz, 2 kW; (c)—200 Hz, 2 kW

long to one single grain. Along with the increasing electromagnetic frequency, the rosette-like primary α-Mg grains have been broken to fragments and these fragments have been gradually varied to the spherical shape. This may be because the higher electromagnetic frequency brings about the induced heat and strengthens the temperature fluctuation of the AZ91D magnesium alloy melt in the stirring chamber and accelerates the necking and remelting effect of the rosette-like primary α-Mg on the secondary arms' root. With the continuously fluid washing and rubbing, the secondary arms separated away from the rosette-like primary α-Mg grains are gradually changed to spherical shape.

4 CONCLUSIONS

1) The shape of primary α-Mg phase looks like a dendrite under conventional solidification condition, which has six second arms on the primary arm symmetrically having a 60° angle to each other, and that the primary α-Mg phases are changed to the fine rosette-like grains or granular grains under electromagnetic stirring condition.

2) If the electromagnetic stirring frequencies are low, there are a large amount of the fine rosette-like primary α-Mg grains and each of them belongs to a single grain in three dimensions and may be rod-like or ellipsoid-like. There are also many spherical primary α-Mg grains in two dimensions, they may belong to a single grain in three dimensions and the grains' orientational differences between them are very small.

3) If the electromagnetic stirring frequencies are high, a lot of the fine rosette-like primary α-Mg grains disappear and are converted into granular grains in two dimensions, and moreover, most of these granular grains belong to different grains in three dimensions.

REFERENCES

[1] China Foundry Association of China Mechanical Engineering Society. Foundry Handbook -Branch Book of Cast Nonferrous Alloys[M]. Beijing: China Machine Press, 2002. 230-238.

[2] Frederick P S, Bradley N L, Erickson S C. Injection molding magnesium alloys[J]. Advanced Materials & Processes, 1988, 134(4): 53-56.

[3] Bradley N L, Wieland R D W, Schafer W J, et al. Method and Apparatus for the Injection Molding of Metal Alloys[P]. US 5040589, 1991.

[4] Decker R F, Carnahan R D, Vining R, et al. Progress in thixomolding[A]. Kirkwood D H, Kapranos P. Proc of the 4th Int Conf on Semi-Solid Processing of Alloys and Composites[C]. University of Sheffield, 1996. 221-225.

[5] Leng T. Thixosystem[A]. Chiarmetta G L, Rosso M ed. Proceedings of the 6th International Conference on Semi-Solid Processing of Alloys and Composites[C]. Turin, Italy: Politecnico DI Torino, 2000. 215-220.

[6] Walukas D M, Vining R E, LeBeau S E, et al. Effect of Process Variables in Thixomolding[A]. Tsutsui Y, Kiuchi M, Ichikawa K. Proceedings of the 7th International Conference on Semi-Solid Processing of Alloys and Composites[C]. Tsukuba, Japan: Japan Society for Technology of Plasticity, 2002. 101-106.

[7] ZHEN Zi-sheng, MAO Wei-min, ZHAO Ai-min, et al. Progress of semi-solid Mg alloy moulding[J]. Special Casting and Nonferrous Alloys, 2001(6): 32-33. (in Chinese)

[8] Kaufmann H, Mundl A. An update on the New Rheocasting—Development work for Al- and Mg- alloys[J]. Die Casting Engineer, 2002, 46(4): 16-19.

[9] Kamado S, Yuasa A, Hitomi T, et al. Effects of stirring conditions on structure and apparent viscosity of semi-solid AZ91D magnesium alloy[J]. Journal of Japan Institute of Light Metals, 1992, 42(12): 734-740.

[10] LI Yuan-dong, HAO Yuan, YAN Feng-yun, et al. Structural evolution of AZ91D magnesium alloy during semi-solid isothermal heat treatment[J]. The Chinese Journal of Nonferrous Metals, 2001, 11(4): 571-575. (in Chinese)

[11] LE Qi-chi, CUI Jian-zhong, LU Gui-min, et al. Microstructure evolution and partially remelting processing of two-phase-region casting AZ91D semisolid slurry ingot[J]. The Chinese Journal of Nonferrous Metals, 2003, 13(6): 1488-1493. (in Chinese)

[12] ZHEN Zi-sheng, MAO Wei-min, CHEN Hong-tao, et al. Effect of electromagnetic stirring process parameters on the microstructure of semi-solid AZ91D alloy[J]. Journal of University of Science and Technology Beijing, 2003, 25(4): 341-345. (in Chinese)

[13] Niroumand B, Xia K. Relationship between microstructural features in a semi-solid processed Al-Cu alloy[A]. Bhasin A K, Moore J J, Young K P, et al. Proc of the 5th Int Conf on Semi-Solid Processing of Alloys and Composites[C]. Golden, Colorado: Colorado School of Mines, 1998. 637-644.

[14] Verrier S, Braccini M, Josserond C, et al. 3D characterization by X-ray tomography of semi-solid aluminum alloys[A]. Chiarmetta G L, Rosso M. Proceedings of the 6th International Conference on Semi-Solid Processing of Alloys and Composites[C]. Turin, Italy: Politecnico DI Torino, 2000. 771-776.

(Edited by LONG Huai-zhong)