

The Application of Aluminum Alloy Rheoforming in Industrial

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Abstract—In light of the application research of aluminum alloy rheological forming, it introduces the application of Rheoforming with several aluminum alloys based on Rheoforming applied research of Key Lab of Near Net Forming in Jiangxi Province in recent years, there are mainly LAO and LSPSF semi-solid slurry preparation process and rheo-extrusion of LSPSF technology, and Rheo-diecasting of LSPSF technology in industrial applications. The results show that the microstructure of the formed parts are nearly spherical or spherical non-dendritic with equivalent diameter below 70 μ m and the form factor up to 0.76, the mechanical properties were significantly better than the ordinary extrusion and die casting.

Keywords—semi-solid; LAO; LSPSF; rheo-extrusion; Rheo-diecasting; Aluminum alloy

I. INTRODUCTION

Semi-solid alloy and composite materials forming processing has been recognized as one of the most promising method for forming light alloy to near net shaped products in the 21st century. Rheological casting is a new controlling technique for solidify microstructures, the key is to obtain semi-solid slurry with uniform distribute of fine spheroidal grains[1,2]. The semi-solid forming technology has been rapid developed in recent years both at home and abroad as its high quality, efficient, low-cost, clean and agile characteristics. Semi-solid forming technology including thixoforming and rheoforming, comparing to the thixoforming, there are following advantages of rheoforming processing: short process, timely local recycling of the waste, energy saving and low consumption, more easily accepted by the small and medium enterprises, has becoming the focal points and hot spots in the academic circles[3 ~ 8]. While semi-solid rheoforming technology and its applications is the focuses of our research.

Recent years, two advanced slurry preparation method have been developed independently based on the basic

principles of rheoforming in our research group: Limited Angular Oscillation (LAO) and Low superheat pouring with a shear field (LSPSF).

II. TWO METHODS OF PREPARATION SEMI-SOLID SLURRY

A. Limited Angular Oscillation (LAO)[9]

LAO method is a special casting process that the high superheated melt flowing through a cylindrical vibration chamber that around its central axis do periodic rotary swing with a certain frequency and amplitude, and swing oscillations and gravity casting formed to achieve local chilling and agitated mixing in the early of the alloy melt solidification. The LAO rheological casting process can effectively prevent the stable formation of the solid shell, semi-solid slurry of light alloy with excellent structures can be prepared, prepare efficiency is 50Kg/min.

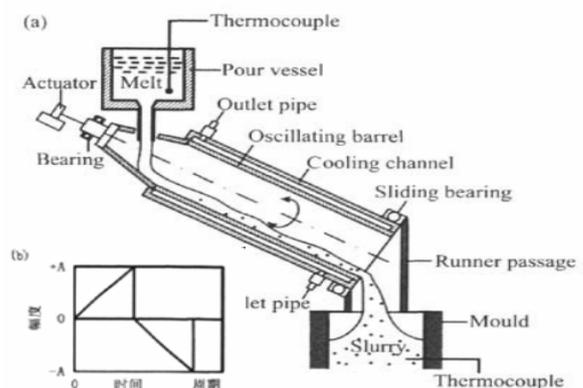


Fig.1 The experimental apparatus schematic of LAO rheological casting(a), oscillation waveform(b).

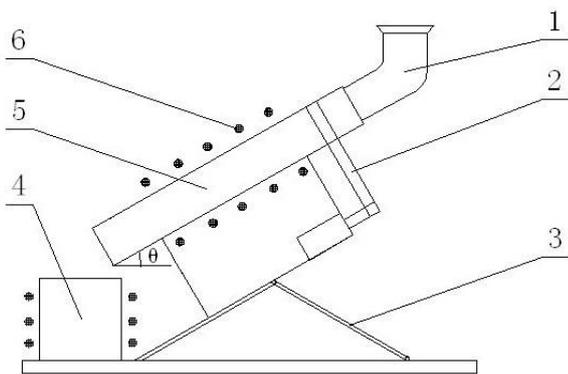
The experimental apparatus of LAO rheological casting process is illustrated in Fig.1, including the oscillation actuator, tundish, oscillation room, slurry collecting crucible,

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independent temperature control system. Oscillation actuator is selected according to the oscillation amplitude and frequency of the vibrating chamber, and the mainly oscillation waveform as shown in Fig.1(b).

B. Low Superheat Pouring with a Shear Field(LSPSF)

The basic principles of LSPSF process is: firstly, by the combined effect of low superheat casting, chilling and agitated mixing at the initial stage of alloy melt solidification, the maximum number of free grain can be obtained in the alloy melt, then control the follow-up of static slow cooling process, semi-solid slurry of good performance can be prepared. The process mainly consists of three steps[10,11]: ① Casting specific superheat alloy melt; ② alloy melt flows through the conveying duct in their own gravity and the rotating of the duct, and to ensure the melt temperature Melt temperature is controlled at the range of lower than the liquidus 1-5 °C when it reach the end of the conveying duct; ③ the static slow cooling of alloy melt with a large number of free crystals in the slurry accumulator. The three main parameters of the process are: a) the composition and superheat degree of the alloy melt; b) the heat dissipating capability and agitated mixing strength; c) the temperature of slurry accumulator. Its process principle is shown in Fig.2.



1.The deflector. 2. Drive unit. 3. Stand. 4. Slurry accumulator. 5. Duct. 6. Heating and cooling system.

Fig.2 process principle diagram of LSPSF rheological casting[10]

The alloy melt flow within the rotational barrel is completed under its own gravity and the delivery tube rotation together. The alloy melt as a whole, the alloy melt at the same time of axial movement along the rotational barrel, since the conveying of the rotation of the tube and the alloy melt on the wall of the adhesion, the alloy melt having the same rotation with the direction of rotation of the rotational barrel trend . Alloy melt having a specific degree of superheat in the shearing force under the action of its own gravity , not the adhesion of the conveyor pipe wall, i.e. does not follow the rotational barrel rotates together , but itself rotating at a specific speed , as show in Fig.3. Alloy melt in the transport tube, the flow of rapidly changing the flow characteristics from the stirring and mixing.

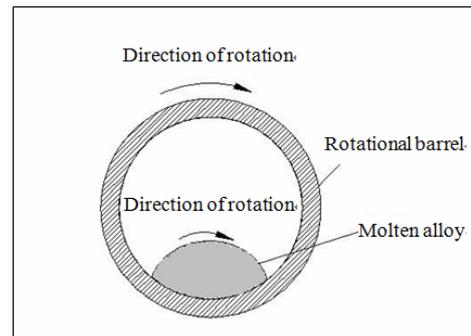


Fig.3 The flow characteristics of the melt in the rotational barrel

Make the process of rotating stirring, the melt solidification process subject to strong disturbance, procure melt formed inside a large number of energy fluctuation, is conducive to the nucleation of the liquid metal in the cold interval . Strong stirring action also speed up the transfer of the solute , increase the nucleation rate . Low superheat pouring , so that the conveyor pipe wall has a strong local chilling effect on the metal melt , under stirring and gravity mixing the chilled liquid is constantly being mixed into the melt , so that the temperature of the melt inside the gradient decreases, within a very short period of time can be in the undercooled state . Transporting the tube wall is coated with a specific coating, can be melt - shaped core provides good nucleation substrate , the process of melt flow , continue to have a melt in contact with the wall , rotation of the rotational barrel for newborn nuclei formation infinite substrate . The local chilling LSPSF process precisely by low superheat pouring duct and mixing of gravity and rotation to maximize the non - spontaneous nucleation .

III. MICROSTRUCTURES EFFECTS OF SEMI-SOLID SLURRY PREPARATION FOR ALUMINUM ALLOY

A. The Microstructures Effects of Semi-solid Slurry by LAO Rheological Casting

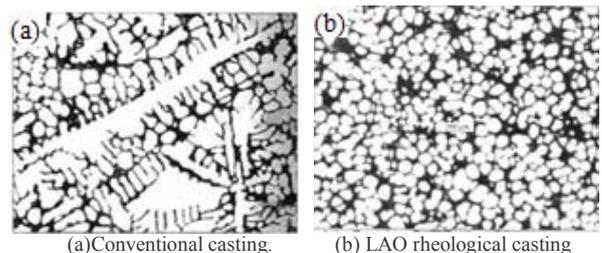


Fig.4 A356 aluminum alloy microstructure under the LAO rheological casting.

Our group has been successfully applied the LAO rheological casting process on the A356 cast aluminum alloy, and has been the best process parameters (including pouring temperature, the oscillation amplitude, the oscillation frequency). Structural characteristics of the semi-solid slurry prepared in this process parameters are as follows: the shape factor of the primary α -Al can be higher than 0.8, the primary α -Al equivalent diameter below 60 μ m. As shown in Fig.4(a), the microstructures for the A356 alloy is typical coarse dendrites, during casting process, the alloy liquid was poured

into a room temperature slurry collecting crucible directly at 665 °C, while the microstructures that obtained under the best LAO rheological casting process conditions, and collecting crucible have been preheated to 500 °C before the slurry pour into it, is fine nearly spherical or spherical non-dendritic[9], as show in Fig.4 (b).

In some of well-known near-liquidus casting process [12 ~ 15], such as NRC[16], CRP,[17] and SSR[18], pouring temperature are close to the liquidus line. While LAO process can improve the casting temperature of A356 aluminum alloy to 665 °C, to get rid of the dependence of the low superheat casting, conducive to the casting operation and temperature control during the actual production, and then get the excellent quality of the semi-solid slurry[19].

B. the Microstructures Effects of Semi-solid Slurry by LSPSF Rheological Casting

Based on LSPSF process methods, our group has successfully prepared a semi-solid slurry of aluminum alloy, including cast aluminum alloy A356, die-casting special aluminum alloy YL112, high-strength cast aluminum alloy 201, wrought aluminum alloy 2024,6082,7075,6063. Fig.5 is water quenched microstructures of semi-solid slurry for A356, YL112, 201, 2024, 6082 and 7075 that prepared for LSPSF methods, and their process conditions and structure characteristics were as shown in Table.1. Fig.5 shown that nearly spherical non-dendritic structure could be produced for such aluminum alloys mentioned above when LSPSF process employed.

TABLE.1 ALUMINUM ALLOY SEMI-SOLID SLURRY PROCESS PARAMETERS RANGE AND SLURRYMICROSTRUCTURE CHARACTERISTICS BY LSPSF PROCESS[20]

Alloy types	Pouring temperature /°C	The average grain size /μm	factor of grain shape	Alloy liquidus temperature /°C
A356	645~660	65	0.84	615
YL112	620~630	66	0.93	595
201	680~690	60	0.78	650
2024	660~680	69	0.76	638
6082	670~690	69	0.78	650
7075	660~680	62	0.78	635

LSPSF technology utilizes a unique method to control the manner and process of alloy solidification, a large number of experimental and production practices demonstrate that the LSPSF technology and other rheological casting has the following advantages[21]: 1) slurry of good quality; 2) high efficiency of slurry preparation; 3) the process parameters adjustment can be flexible; 4) large range of pouring temperature; 5) a wide range of applicable alloy; 6) separation of slurry preparation and slurry forming. Therefore, the LSPSF process has a good prospects and potential for industrial applications

IV. APPLICATION OF RHEOFORMING PROCESS

A. LSPSF Rheo-extrusion Casting[21 ~23]

International semi-solid slurry directly forming process mainly include the rheo-diecasting, rheo-extrusion casting and rheology rolling. Rheo-extrusion casting is a new material forming technology, that set rheological casting and squeeze casting as a whole, utilizes rheological properties of semi-solid slurry to fill, and solidify under pressure, It combines the dual advantages of semi-solid forming and squeeze casting, which's structural component characterized by high safety and high density, is one of the main direction of the rheoforming technology development. Combined with LSPSF technology and direct squeeze casting process, LSPSF rheo-extrusion casting process has been developed by our group. In this paper LSPSF rheo-extrusion casting process could be discussed and employed the rheological squeeze casting deformation of 7075 aluminum alloy cup-shaped parts and the A356 cast aluminum alloy automobile wheels as example.

7075 wrought aluminum alloy semi-solid slurry directly squeeze cast cup-shaped parts shown in Fig.6, in full compliance with the requirements of industrial products. Microstructure can be drawn from Figure 7 , rheo-extrusion casting can be obtained regardless of the uniform microstructure, the primary α-Al is a typical small near-spherulites . Similar to the microstructure of the microstructure of the three parts of the parts a, b, e and the original semi-solid slurry , substantially no change. parts c of the microstructure occurred plastic deformation, is elongated along the slurry flow direction. Parts of the microstructure of the workpieced , small grain between the relatively large primary α-Al grain, these grains are not present in the original semi-solid slurry , and the coarse

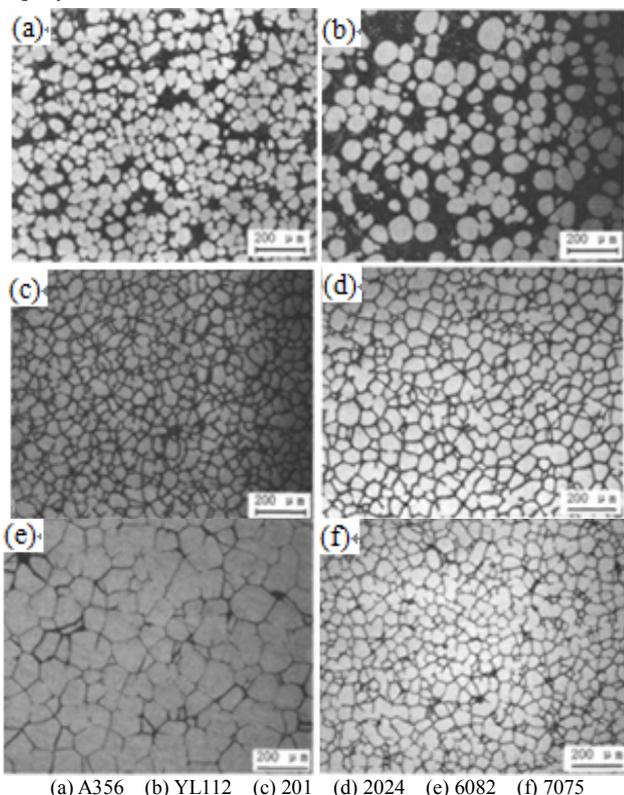
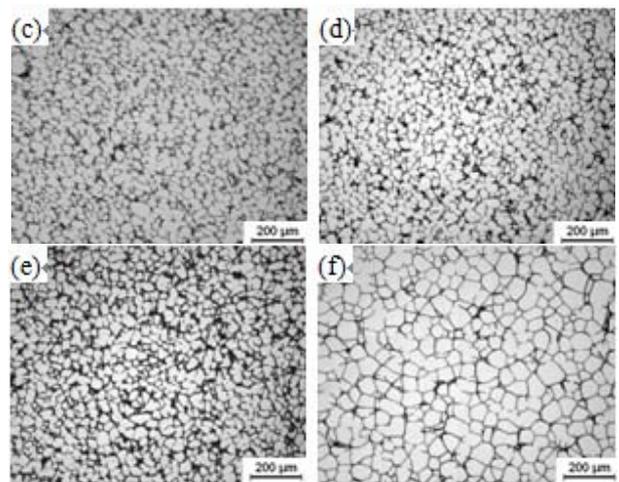
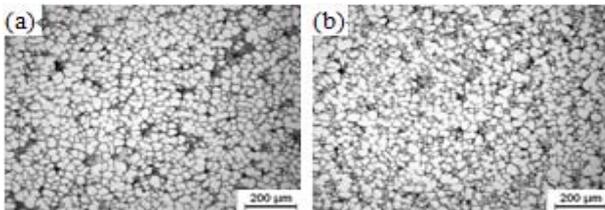


Fig.5 Typical aluminum alloy semi-solid slurry microstructure by LSPSF process[20]

primary α -Al grains are connected to each other, forming irregular grains. These phenomena extrusion process caused by the squeeze casting mold structure and direct punch. Part e at the bottom, a very small force by the punch, and the slurry is substantially no flow, a, b parts of the inner wall and an outer wall substantially parallel to, the force is also small, so the three parts forming the microstructure and the microstructure of the semi-solid slurry is basically the same. Part c in the turning position of the part shape, the portion near the primary α -Al occurs plastically deformed, the direction of the slurry flow is elongated. part d of semi-solid slurry by the extrusion pressure is very large, filling post and packing during recrystallization phenomenon occurs, resulting in some very fine grains, at the same time the primary α -Al in a lot of compression occurs under welding, forming some very irregular grain. Quantitative analysis showed that: the average diameter of the primary α -Al equivalent circle is $63\mu\text{m}$, average shape factor is 0.75, and the inter-granular segregation is much weaker than conventional squeeze casting.



Fig.6 Cup-shaped parts by rheo-extrusion casting



(a~e) the microstructure corresponding parts in Figure 5, (f) Microstructure of semi-solid slurry

Fig.7 Microstructure of 7075 aluminum alloy cup-shaped parts in different parts by rheo-extrusion casting

The A356 aluminum alloy near-hub part for auto that produced by semi-solid slurry rheo-extrusion casting process is shown in Fig.8, in which the thickness at positions (a) (b) (c) in Fig.8(c) were 8mm, 6mm and 8mm respectively, it is also the new product that our group committed to research currently. Process parameters that have been identified and its corresponding mechanical properties are shown in Table.2, sampling location is in position (c). In general, the mechanical properties has not yet reached the design requirements, but still an improvement compare with that under normal casting conditions, Moreover, there will also be significantly improved after heat treatment. Fig.9 showing the different parts' microstructures of the casting, and is also typical fine spherical grains, in which the most uniform and fine microstructures appears in position (b), and here is also squeezed by the largest shear force.



Fig.8 near-hub part for auto by rheo-extrusion casting. (a)near-hub part for auto (b) Mold condition

TABLE.2 PROCESS PARAMETERS AND MECHANICAL PROPERTIES OF NEAR-HUB PART FOR AUTO BY RHEO-EXTRUSION CASTING (NO HEAT TREATMENT)

Semi-solid pulp temperature / $^{\circ}\text{C}$	Pouring temperature / $^{\circ}\text{C}$	Specific pressure /MPa	Dwell time /s	Tensile strength /MPa	Elongation /%
630~650	605~610	22	15	187	10.87
630~650	605~610	22	15	183	9.01

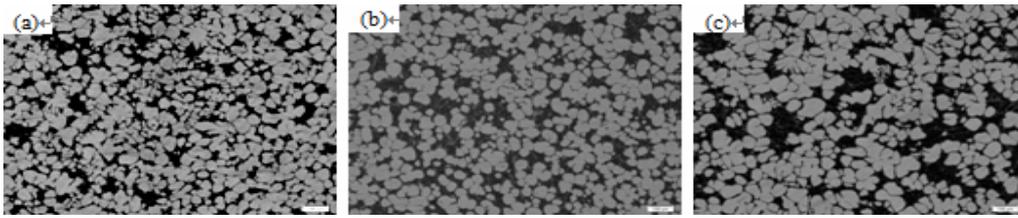


Fig.9 microstructures of near-hub part for auto in different parts by rheo-extrusion casting

B. LSPSF rheo- diecasting technology[20,21]

Combined with rheological LSPSF casting technology and high-pressure casting technology (a high pressure diecasting, HPDC), we have developed a rheological die casting (Rheo-diecasting, the RDC) process[24 ~ 26], and successfully forming the semi-solid slurry directly, the main equipment we employed are LSPSF pulper machine and the conventional die casting machine. Semi-solid slurry preparation stage (the first solidification) and the slurry forming stage (including slurry filling, solidification and preparation for next injection and the second solidification) are in parallel. The practice shows that the slurry preparation time is shorter than the slurry forming, so it is time to decide an RDC process from the slurry forming. We have studied low solid fraction semi-solid slurry rheo-diecasting-direct for YL112 alloy, and developed the low porosity die-casting process for these alloy.

Fig.10 is a support parts by die-casting and its density, can

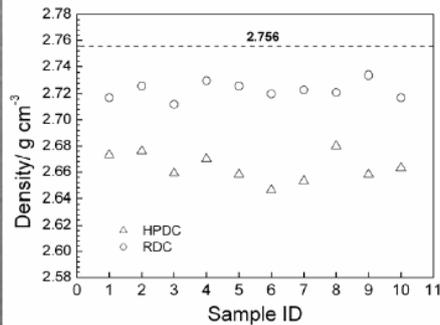
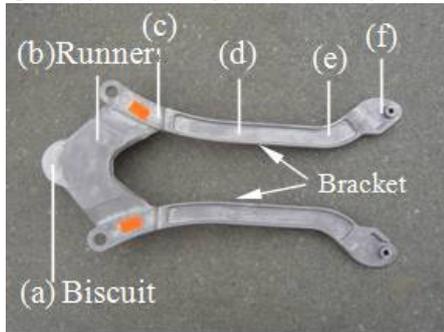


Fig.10 Stent die-casting and its density

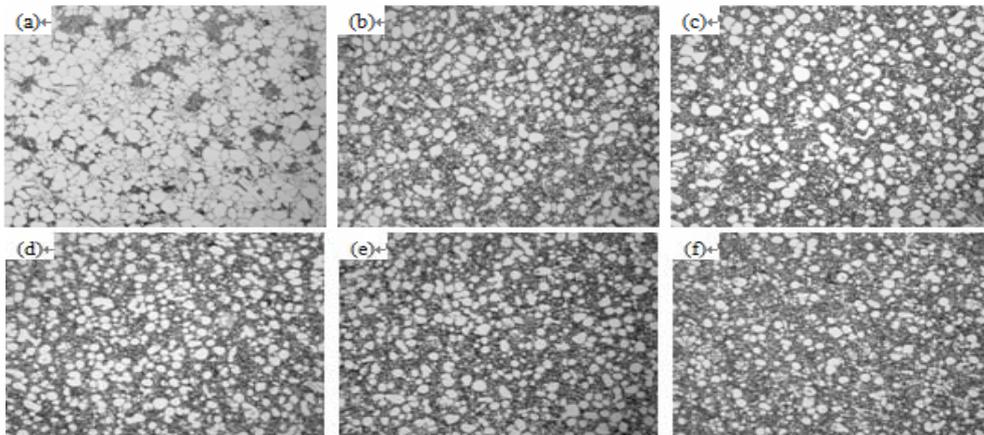


Fig.11 The microstructure of stent die-castings in different parts

be seen that the density distribution is much concentrated, but its compactness worse than the theoretical value of rheo-diecasting. Fig.11 shows the microstructures in different parts of the die-casting support part. Generally, the primary solid phase by rheo-diecasting is fine and uniform, and will not change much when the casting thickness change. And during the secondary solidification, semi-solid slurry will occurs volume solidification in the mold cavity, Microstructures distribution of the casting, whether observed from the cross-sectional or longitudinal, are uniformly, the intermetallic compounds and eutectic Si are fine.

The mechanical properties of YL112 alloys in different conditions as shown in Table.3, compared with traditional die-casting: though there is low tensile strength of the Rheo-diecasting, but the yield strength and elongation have been greatly improved, especially the elongation increased by 53.6%; after T5 treatment, the tensile strength and yield strength has improved significantly, while the elongation

decline, T6 treatment can effectively improve the mechanical properties of the RDC casting, and the elongation can reach the highest point of 5.4% after T6 (solution 3min); Finally, both the strength and ductility have reached a good level after T6 (solution processing 30min) treatment.

TABLE.3 THE MECHANICAL PROPERTIES OF YL112 ALLOY WITH DIFFERENT CONDITIONS

Process conditions	Yield strength /MPa	Tensile strength/ MPa	Elongation /%
HPDC, F	147	272	2.8
RDC, F	164	263	4.3
RDC, T5	193	282	3.2
RDC, T6×3min	217	309	5.4
RDC, T6×30min	246	324	4.8

V. CONCLUSION

Successfully developed LAO technology and LSPSF process pulping equipment that with independent intellectual property, and prepared successfully the semi-solid slurry of aluminum alloys: A356, YL112, 201, 2024, 6061, 6082, 7075, 6063. LSPSF pulping process and the extrusion process and diecasting process combined, we successfully developed the LSPSF rheo-extrusion casting technology and LSPSF rheo-diecasting technology, and the success of these two technologies used in near-hub part for auto, cup-shaped parts and parts of stents, received a good microstructure and mechanical properties to achieve the requirements of industrial applications, but near-hub part for auto forming process to be further improved.

REFERENCES

- [1] FLEMINGS M C. Behavior of metal alloys in the semi-solid state[J]. Metallurgical Transactions A, 1991, 22(4): 957-981
- [2] LUO Shou-jing, TIAN Wen-tong, XIE Shui-sheng, MAO Wei-min. Technology and applications of semi-solid forming[J]. The Chinese Journal of Nonferrous Metals, 2000, 10(6): 765-769.
- [3] Xie Shui-sheng, Huang Sheng-hong. Semi-solid metal processing technologies and applications[M]. Beijing: Metallurgical Industry Press, 1999
- [4] Luo Shou-jing, Jiang Ju-fu, Du Zhi-ming. New research development, industrial application and some thinking of semi-solid metal forming[J]. Chinese Journal Of Mechanical Engineering, 2003, 39(11): 52-60.
- [5] Mao Wei-min. Semi-solid metal forming technology[M]. Beijing: China Machine Press, 2004
- [6] Kang Yong-lin, Mao Wei-min, Hu Zhuang-qi. Theory and technology of semi-solid processing of metallic materials[M]. Beijing: Science Press, 2004
- [7] Guan Ren-guo, Ma Wei-min. Metal semi-solid forming theories and techniques [M], Beijing: Metallurgical Industry Press, 2005.
- [8] FAN Z. Semisolid metal processing[J]. Int. Mater. Rev., 2002, 47(2): 1-37.
- [9] Guo Hong-min, Zhang Ai-sheng, Liu Xu-bo. Angular oscillation rheocasting process and its applications[C]. Special Casting & Nonferrous Alloys, 2011 Annual Meeting Issue: 371-373
- [10] GUO H M, YANG X J. Efficient refinement of spherical grains by LSPSF rheocasting process[J]. Material Science and Technology, 2008. 24(1): 55-63.
- [11] GUO H M, YANG X J, HU B. Low superheat pouring with a shear field in rheocasting of aluminum alloys[J]. Journal of Wu-han University of Technology-Materials Science Edition, 2008, 23(1): 54-59.
- [12] XIA K, TAUSIG G. Liquidus casting of a wrought aluminum alloy 2618 for thixoforming[J]. Mater Sci Eng A, 1998, 246(1/2): 1-10.
- [13] DONG J, CUI J Z, LE Q C, LU G M. Liquidus semi-continuous casting, reheating and thixoforming of a wrought aluminum alloy 7075[J]. Mater Sci Eng A, 2003, 345(1/2): 234-242.
- [14] LIU Zheng, MAO Wei-min, ZHAO Zhen-duo. Effect of pouring temperature on semi-solid slurry of A356 Al alloy prepared by weak electromagnetic stirring[J]. Transactions of Nonferrous Metals Society of China, 2006, 16(1): 71-76.
- [15] ZHANG Xiao-li, LI Ting-ji, XIE Shui-sheng, JIN Jun-ze. Semisolid processing AZ91 magnesium alloy by electromagnetic stirring after near-liquidus isothermal heat treatment[J]. Mater Sci Eng A, 2008, 475(1/2): 194-201.
- [16] KAUFMAN H, WABUSSEG H. Metallurgical and processing aspects of the NRC semi-solid casting technology[J]. Aluminum, 2000, 76(1/2): 70-75.
- [17] APELAN D, PAN Q Y, FINDO M. Low cost and energy efficient methods for the manufacture of semi-solid (SSM) feedstock[J]. Die Casting Engineer, 2004 48(1): 22-28.
- [18] LEE JIN-KYU, KIM SHAE. Modeling of in-ladle direct thermal control rheocasting process[J]. Mater Sci Eng A, 2007, 449/451: 680-83.
- [19] Guo Hong-min, Yang Xiang-jie, Luo Xue-quan. Effects of angular oscillation on semi-solid microstructure of A356 aluminum alloy[J]. The Chinese Journal of Nonferrous Metals, 2009, 19(12): 2106-2111.
- [20] Guo Hong-min, Yang Xiang-jie. Overview of LSPSF rheocasting process and its applications[J]. Special Casting & Nonferrous Alloys, 2008 Annual Meeting Issue: 355-359.
- [21] Guo Hong-min. Investigation on technique and theory of rheoforming for semi-solid aluminum alloys[D]. Nanchang: Nanchang University, 2007
- [22] GUO H M, YANG X J. Preparation of semi-solid slurry containing fine and globular particles for wrought aluminum alloy 2024 [J]. Transactions of Nonferrous Metals Society of China, 2007, 17(4): 799-804.
- [23] GUO H M, YANG X J, ZHANG M. Microstructure characteristics and mechanical properties of rheoformed wrought aluminum alloy 2024[J]. Transactions of Nonferrous Metals Society of China, 2008.
- [24] Guo Hong-min, Yang Xiang-jie. Microstructures characteristics of YL112 aluminum alloy produced by rheo-diecasting process[J]. The Chinese Journal of Nonferrous Metals, 2008, 18(3): 400-408.
- [25] Guo Hong-min, Yang Xiang-jie. Heat treatments and mechanical properties of YL112 aluminum alloy produced by rheo-diecasting process[J]. The Chinese Journal of Nonferrous Metals, 2008, 18(3): 394-399.
- [26] GUO H M, YANG X J, HU B, et al. Rheo-diecasting process for aluminum alloys[J]. Journal of Wu han University of Technology-Materials Science Edition, 2007, 22(4): 590-595.