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REVIEW

Research Status of Preparation Technique of Aluminum Alloy Semi-solid Slurry

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Abstract: Semi-solid processing (SSP) technique is an important method for metal casting. Products made by SSP technique have advantages such as small solidification shrinkage, high dimensional accuracy of castings, fast forming speed, high productivity, and good mechanical properties. Aluminum alloy products produced by SSP technique can be heat-treated. The mechanical properties of the products after heat treatment are similar to those of steel, but they have the lighter mass and are widely used in many fields. Semi-solid slurry preparation technique is one of the key techniques in the field of aluminum alloy semi-solid forming, which determines the industrial application of semi-solid forming and also has significant impact on the quality of aluminum alloy semi-solid slurry. Semi-solid slurry preparation technique with the continuous development has become the emerging technique in the field of metal processing. The principles, advantages and disadvantages of various semi-solid slurry preparation techniques for metal materials were reviewed, and the future trends of semi-solid slurry preparation techniques were predicted.

Key words: aluminum alloy; semi-solid forming; semi-solid slurry preparation techniques

Aluminum alloy semi-solid processing (SSP) technique was firstly applied in the 1970s. SSP technique was proposed due to the good strengthening effect of non-dendritic spheroidal microstructure, and became the new branch in the field of aluminum alloy forming[1–2]. From the early 1980s to the early 1990s, with the development of computer technique and numerical simulation methods, in-depth research on aluminum alloy SSP technique was conducted[3–4]. At the same time, some international renowned enterprises had also begun to invest a lot of capital and human resources in related research[5]. Since the beginning of the 21st century, aluminum alloy SSP technique has been widely used and promoted[6]. Aluminum alloy SSP technique has made remarkable progress in aerospace, automobile manufacturing, communication equipment shell, and other fields[7–11], thus gradually becoming an important method to replace traditional processing methods.

With the development of aluminum alloy SSP technique, the key techniques mainly include the preparation of semi-solid alloy slurry and the optimization of forming process parameters. The preparation of high quality semi-solid alloy slurry is one of the crucial problems in the SSP technique of aluminum alloy[12–13].

The basic principle of semi-solid slurry preparation of aluminum alloy is to make the dendrite structure of aluminum alloy into the semi-solid state with a certain proportion of non-dendrite spherical solid structure and liquid structure. The semi-solid slurry has high fluidity and viscosity, and can be processed by die casting, extrusion casting, etc. Compared with traditional casting, the products prepared by SSP technique can be heat-treated and have the advantages of high strength and good toughness[14–16].

Many experts[17–21] have developed various methods for preparing aluminum alloy semi-solid slurry based on the basic principle of aluminum alloy semi-solid slurry. The principles of these semi-solid slurry preparation techniques are different, and the qualities and ability to generate semi-solid microstructure are also different. Additionally, the equipment required for each semi-solid slurry preparation technique

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varies significantly, leading to different difficulties for industrial application.

This research reviewed the principles of various semi-solid slurry preparation techniques for aluminum alloy and analyzed the formation mechanisms of semi-solid microstructures. The issues with the quality of slurry preparation and the challenges in industrial applications of these techniques were presented. Finally, the development trend of semi-solid slurry preparation technique was proposed.

1 Semi-solid Slurry Preparation Method

Depending on the morphology during the preparation process, the preparation methods for semi-solid aluminum alloy slurries include solid state processing and liquid state processing.

1.1 Solid state processing method

Solid state processing method is to heat the solid alloy until it is partially melted, and then mechanical or chemical methods are used to make it disperse evenly. Finally, the semi-solid alloy slurry is obtained. The representative methods include strain-induced melt activation method and isothermal heat treatment method.

1.1.1 Strain-induced melt activation method

In 1983, the concept of solid state deformation of cast metals before partial melting was firstly proposed, and was called strain-induced melt activation (SIMA) method[22–24]. As shown in Fig. 1, SIMA technique is started with the hot working of the metal (such as extrusion, rolling, forging, and other methods) at temperatures below the solid phase line to produce the oriented grain structure. Then, strain is introduced through drawing, forging, rolling, compression, or cold working of upsetting, which causes severe deformation of the metal microstructure. And abundant residual stress remains in the severely deformed microstructure. When the deformed metal is reheated to the two-phase zone state, the severely deformed microstructure will partially melt to form spherical microstructure. Finally, the semi-solid slurry with non-dendrite microstructure is formed by rapid cooling. The essence of strain induction is that the transition from dendrite to spherical structure does not occur directly during or after the induced deformation, but requires to heat the induced deformation structure to the two-phase zone state, producing partial melting and eventually forming semi-solid structure.

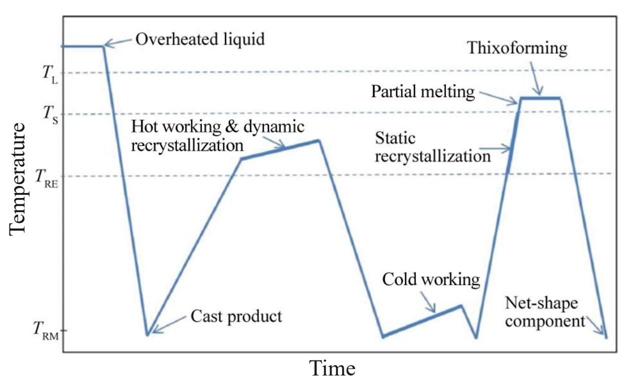

Fig.1 Schematic diagram of SIMA method[23]

On the basis of SIMA technique, recrystallization and partial melting technique was developed in 1992, which used room temperature deformation instead of cold work, simplifying the deformation process[25–28]. But it had no essential difference with SIMA technique. Later, many researchers made some improvements for SIMA technique, but did not break away from the scope of SIMA technique[29].

1.1.2 Semi-solid isothermal heat treatment method

Semi-solid isothermal treatment (SSIT) emerging in the 1990s belongs to semi-solid slurry preparation method. During the process of SSIT, solid-state alloys requires to be isothermally treated for a long time, and the dendrite structure of the alloy will gradually melt at the grain boundary, forming non-dendrite spheroidized structure. Finally, the semi-solid structure with the coexistence of liquid and solid is formed[30–32]. The preparation of semi-solid slurry by SSIT method is simple and maneuverable without melt oxidation and other secondary pollution, which opens up the new direction for the preparation of semi-solid slurry. Wu et al[33] studied the microstructure evolution process of semi-solid Mg-10Gd-3Y-0.5Zr alloy during isothermal heat treatment, and found that the initial particles are continuously coarsened with the prolongation in holding time, and the coarsening rate is decreased with the increase in isothermal temperature. As shown in Fig. 2, the optimum temperature of SSIT of Mg-10Gd-3Y-0.5Zr alloy is 610–620 °C, and the optimum holding time is 20–40 min.

Jarfors et al[34] studied the microstructure evolution of semi-solid Mg-14Al-0.5Mn alloy during SSIT. The results shows that the microstructure of the cast alloy is composed of α-Mg, β-$Mg_{17}Al_{12}$, and a few Al-Mn compounds. The solid phase and liquid phase reach the state of dynamic equilibrium. As shown in Fig.3, with the prolongation in holding time, the particle size of Mg-14Al-0.5Mn alloy firstly decreases and then gradually increases, and the solid fraction gradually decreases.

Although solid-state processing methods for producing semi-solid aluminum alloy slurries are straightforward and simple, the quality of the semi-solid slurry is highly dependent on the process parameters. Moreover, the slurries produced by these methods are exclusively suitable for thixoforming processes, which may lead to lower production efficiency.

1.2 Liquid state processing method

The liquid state processing of aluminum alloy semi-solid slurry requires to heat the solid alloy to the liquid state. The common processing methods for semi-solid aluminum alloy slurries include rotary enthalpy balance method, new rheological casting method, double helix mixing method, shear low temperature pouring method, inverted cone channel pouring method, serpentine channel method, self-incubation method (SIM), enthalpy compensation method (ECM), gas induction method, ultrasonic vibration method, mechanical

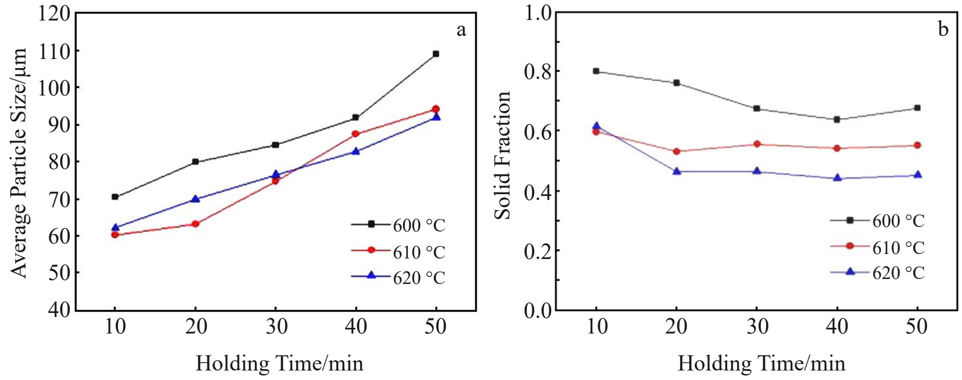

Fig.2 Effects of isothermal temperature and holding time on average primary particle size (a) and solid fraction (b) of Mg-10Gd-3Y-0.5Zr alloy[33]

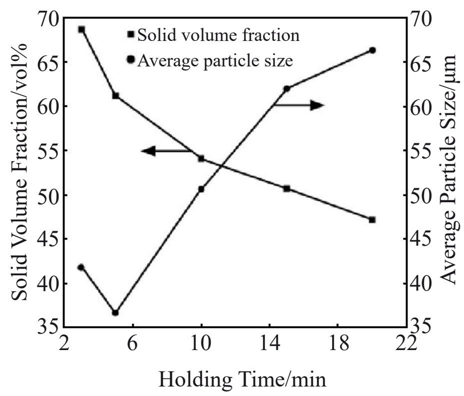

Fig.3 Changes of solid volume fraction and average particle size with holding time for Mg-14Al-0.5Mn alloy at 520 °C[34]

mixing method, wave-shaped vibration tilting plate method, and straight pipe method.

1.2.1 Rotary enthalpy balance method

Swirl enthalpy equilibration device (SEED) method is the rotary enthalpy balance method proposed by Alcan to prepare aluminum alloy semi-solid slurry. The principle of SEED is shown in Fig.4. Molten liquid aluminum alloy is firstly poured into the crucible, and the swirling device drives the crucible to rotate. The liquid aluminum alloy begins to crystallize in the form of dendrites in the swirling crucible, but the resulting dendrites are soon broken by the rotating melt. Subsequently, the broken dendrites begin to aggregate and form spherical solid structures under the action of the rotating melt. At this time, the aluminum alloy in the crucible is in the state of solid-liquid coexistence. When the solid structure reaches the certain proportion, it is poured into the casting mold to obtain the product with semi-solid structure[35–36].

The commonly used rotation drive ways for preparing semi-solid slurry by rotary enthalpy balance method include electromagnetic stirring method[37] and eccentric rotation method[38]. Electromagnetic stirring method requires high-cost special equipment, and its stirring effect of the crucible center is weak, reducing the solid-microstructure generation ability of the melt center and making the prepared semi-solid slurry microstructure nonuniform. So the electromagnetic stirring method is generally used for the preparation of small volume semi-solid slurry. The eccentric rotation method is simple, but the unbalance of eccentric rotation restricts the rotation speed, which has a great effect on the destruction of dendrites and the production of spherical solid structures during melt crystallization, resulting in the failure to prepare of semi-solid slurry with high solid fraction.

1.2.2 New rheological casting method

The semi-solid slurry prepared by mechanical stirring was firstly used in semi-solid rheological casting. The preparation of semi-solid slurry by mechanical stirring has low efficiency and will cause secondary pollution to slurry. Japan UBE Company developed the new rheological casting method (NRC), and the principle of NRC is shown in Fig. 5. The preparation of semi-solid slurry by NRC technique requires three steps. Step [1] is cooling the inclined plate ([1]-A) or

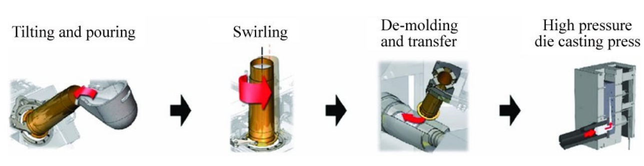

Fig.4 Schematic diagram of SEED technique[35]

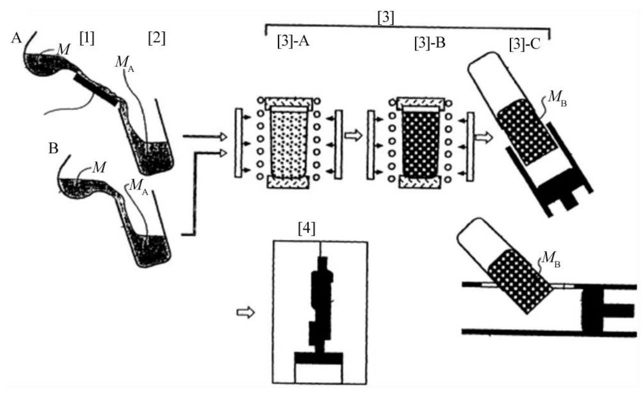

Fig.5 Schematic diagram of NRC technique[39]

directly pouring the molten alloy into the inclined crucible ([1]-B). In step [2], the crucible is raised to the vertical position. In step [3], the controlled cooling solid content is gradually increased. In step [3]-C, the crucible is inverted and the semi-solid slurry is moved into the die casting machine mold.

In NRC technique, the molten alloy is poured into the crucible through the cooled inclined plate, and then a large number of primary α-Al crystal nuclei will form when the superheated molten alloy encounters the supercooled inclined plate. α-Al crystal nuclei are also produced during the controlled cooling process of metal melt, and gradually grow. The solid phase content gradually increases, and the material is in semi-solid state.

The preparation of semi-solid slurry by NRC technique belongs to the inclined plate casting process, which has the characteristics of uniform distribution of primary α-Al, low cost, and strong operability[39]. Researchers improved the NRC technique[40] by introducing vibration of the inclined plate and rotation of the crucible to enhance the performance of semi-solid slurry prepared by NRC technique.

Fig.6 shows the effect of inclined plate vibration on A356 aluminum alloy. As shown in Fig. 6, applying vibration to inclined plate can reduce the size of primary α-Al grains in melt. Table 1 shows the influence of different crucible states

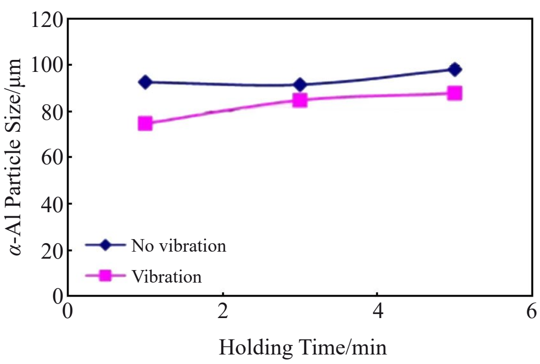

Fig.6 Influence of inclined plate vibration on A356 aluminum alloy[40]

Table 1 Influence of different crucible states on A356 aluminum alloy[40]

Crucible condition	Temperature/°C	α-Al partical size/μm	Shape factor
1	630	121±16	2.4
2	630	102±14	2.7
1	650	125±28	1.8
2	650	109±24	2.8
3	630	70±18	1.4
4	630	75±21	1.5

Note: 1-crucible rotates at 200 r/min without cooling inclined plate; 2-crucible does not rotate without cooling inclined plate; 3-crucible rotates at 200 r/min with cooling inclined plate; 4-crucible does not rotate with cooling inclined plate.

on A356 aluminum alloy. It can be seen from Table 1 that the primary α-Al particle size is larger without cooling inclined plate. Adding the cooling inclined plate can reduce the primary α-Al particle size. The rotating crucible has a certain effect on the particle size of primary α-Al. The simultaneous use of rotating crucible and cooling inclined plate can obtain finer semi-solid microstructure.

1.2.3 Double spiral mixing method

Ji et al[41] from Brunel University, UK, invented twin-screw rheomoulding process (TRP) of semi-solid slurry technique based on the principle of injection molding machine. As shown in Fig. 7, TRP device is mainly composed of metal melt crucible, spiral stirring rod, cylinder, and other parts. Two engaged spiral stirring rods rotate relatively to each other. The metal melt at the certain temperature flows into the cylinder from the crucible and begins to nucleate and crystallize. The dendrite structures formed in the metal melt are destroyed under the action of gravity and shear of the rotating stirring rods, forming the non-dendrite spheroidal semi-solid structures. The semi-solid slurry is directly injected into the die casting machine to process the semi-solid product. TRP technique can continuously prepare semi-solid slurry with the advantage of high production efficiency. But the semi-solid slurry after mixing can not be fully mixed, resulting in uneven product microstructure, and affecting the quality of product.

Zhu et al[42] prepared semi-solid slurry of AZ91D alloy through the double helix mixing process. According to the microstructure of AZ91D alloy at different mixing speeds in Fig. 8, it can be seen that TRP technique can effectively prepare semi-solid slurry, but the microstructure distribution is not uniform.

1.2.4 Shear low temperature pouring method

Guo[43] and Luo[44] et al proposed the semi-solid slurry preparation technique of low superheat pouring with a shear field (LSPSF). The technical principle of LSPSF is shown in Fig.9. The alloy melt at the certain temperature is poured into the pulping device from the gate. And under the rotation of gravity and the drum, the melt begins to nucleate and crystallize. The initial dendrite structure will be broken by the

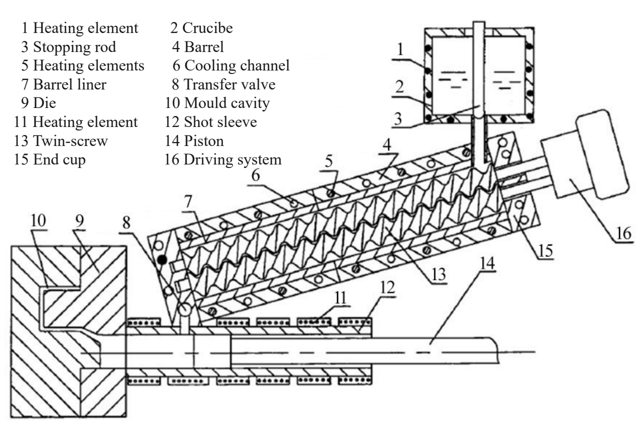

Fig.7 Schematic diagram of TRP technique[41]

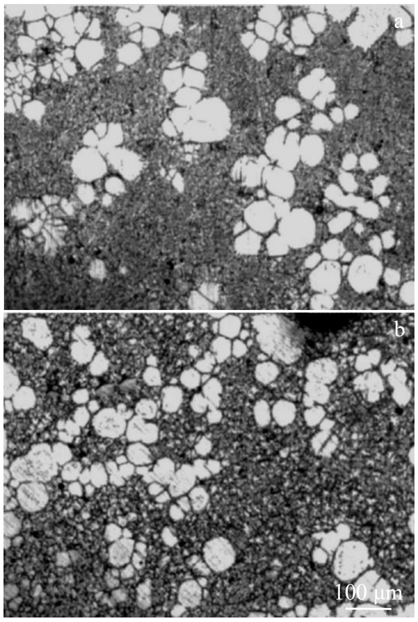

Fig.8 Microstructures of AZ91D alloy at different stirring speeds: (a) 300 r/min and (b) 500 r/min

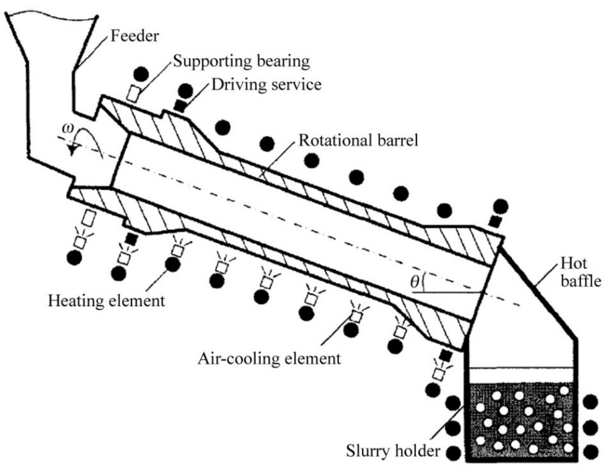

Fig.9 Schematic diagram of LSPSF technique[44]

shear action caused by the rotation of the melt, gradually forming the non-dendrite spherical structure. The melt with the non-dendrite structure is mixed in the collection vessel and slowly cooled to obtain the semi-solid slurry. Semi-solid slurry can be prepared continuously by LSPSF technique, which has the characteristics of high production efficiency and low cost.

Guo et al[45–46] conducted a lot of research on LSPSF technique, and used LSPSF technique to prepare A380 semi-solid slurry. As shown in Fig.10, the semi-solid microstructure of A380 alloy prepared by LSPSF technique at different pouring temperatures is obvious non-dendrite spheroidization structure, and it has good spheroidization effect and uniform microstructure distribution.

1.2.5 Inverted cone channel pouring method

Yang et al[47–48] from University of Science and Technology Beijing proposed the semi-solid slurry preparation technique of inverted cone channel pouring process (ICP). The principle of ICP technique is shown in Fig.11. The alloy melt is heated to the certain temperature, and then poured into the inverted conical channel. The inverted conical channel makes it easier for the melt to flow out along the inner wall of the channel. When the overheated alloy melt encounters the cool inverted cone channel wall, a large number of primary α-Al crystal nuclei are formed. The primary α-Al crystal nuclei will be attached to the inner wall of the inverted cone channel. As the melt continuously erodes the inner wall of the inverted conical pipeline, the newborn α-Al crystal nucleus is brought into the melt, resulting in a large number of primary α-Al nuclei inside the melt. The primary α-Al crystal nuclei in the supercooled alloy melt continue to grow, eventually forming the semi-solid microstructure with solid-liquid coexistence. ICP technique can continuously prepare semi-solid slurry, which is characterized by short process, simple equipment, and low cost.

Fig. 12 shows the microstructure of semi-solid 7075 aluminum alloy prepared by ICP technique. Under the same conditions, the larger the channel taper, the smaller the primary α-Al grain size. But over-large channel taper will affect the melt flow performance, so the channel taper should be selected appropriately.

1.2.6 Serpentine channel method

Chen et al[49–50] from the University of Science and Technology Beijing proposed the serpentine channel process (SCP) technique for preparing semi-solid slurry. SCP technique is the non-stirred semi-solid pulping technique and

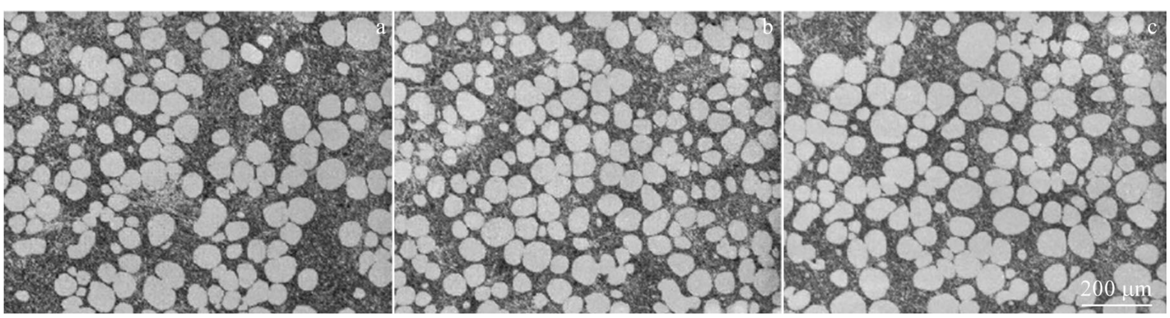

Fig.10 Microstructures of semi-solid A380 alloy prepared by LSPSF technique at different pouring temperatures[46]: (a) 630 °C; (b) 620 °C; (c) 625 °C

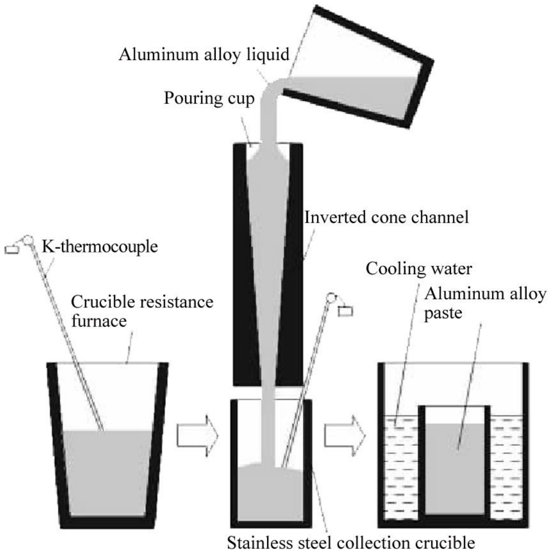

Fig.11 Schematic diagram of ICP technique[47]

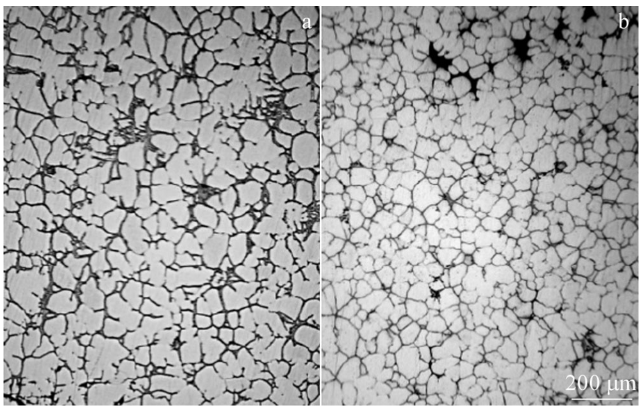

Fig.12 Microstructures of 7075 aluminum alloy semi-solid slurry with different channel tapers[47]: (a) 2° and (b) 6°

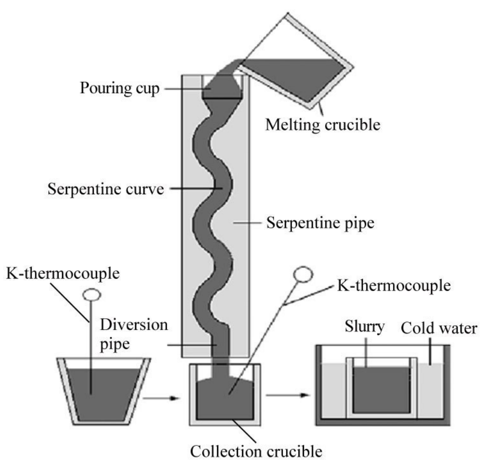

Fig.13 Preparation of A356 aluminum alloy semi-solid slurry by SCP technique[49]

its working principle is shown in Fig. 13. SCP method is to pour the alloy melt into the serpentine tube. The melt is cooled rapidly and the nuclei are formed[51–53]. The curved pipe can further promote the nucleation ability of the melt. Part of the formed nuclei continues to grow or form new nuclei in the melt, and the other part adheres to the pipe wall and continues to grow. Chen et al[51] believe that the semi-solid slurry prepared by the serpentine channel method has the effect of self-stirring in the alloy melt, so the non-dendritic spheroidized structure can be formed directly from the melt.

Fig. 14 shows the metallographic microstructure at different bends of the serpentine pipeline. It can be seen that the serpentine channel method for preparing semi-solid slurries results in the amorphous semi-solid microstructure. The effects of the number and the diameter of the bends on the primary α-Al morphology and grain size were investigated. Results show that the more the bends, the better the primary α-Al morphology; the larger the diameter of the bends, the better the primary α-Al morphology and the smaller the grain size.

1.2.7 SIM

SIM is a new semi-solid pulping technique[54–57]. SIM technique involves melting two different metals and mixing them to form the alloy melt. Due to different physical properties of the two metals, such as melting point and surface tension, a large number of nuclei begin to form in the alloy melt after mixing. The melt is then poured into the collector through the inclined deflector. The melt is split into two parts as it is poured into the diverter, and then the split parts are merged together again. The secondary nucleation capacity is improved by splitting and merging the melt. The coarse dendrites will be broken in the process of melt flowing on the deflector, and the crystals with smaller grain size will be obtained. Prepared melt is thermally preserved in liquid-solid

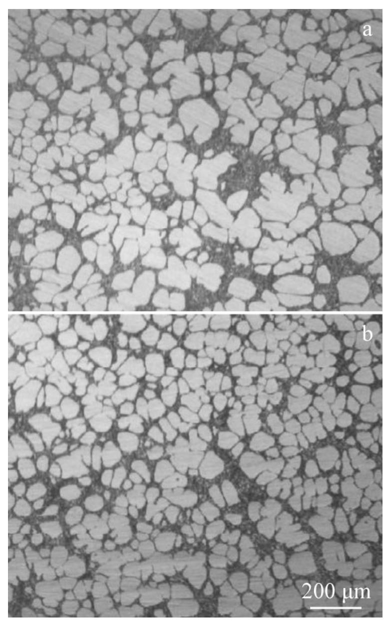

Fig.14 Microstructures of quenched A356 aluminum alloy semi-solid slurries prepared by serpentine pipe with 3 bends and bend diameter of 20 mm at different pouring temperatures[49]: (a) 680 °C; (b) 660 °C

phase, and non-dendrite spherical structures are formed inside the melt, forming semi-solid structures. SIM technique prepares semi-solid slurry in a simple and maneuverable way. The principle of SIM technique is shown in Fig.15.

Xing et al[58] investigated the effect of SIM technique on grain refinement of AM60 magnesium alloy, and the results are shown in Fig. 16. The alloy microstructure prepared by SIM technique has smaller grain size and obvious non-dendritic microstructure. However, the grain shape is mostly polygonal, and the non-dendritic spheroidization effect is ordinary.

1.2.8 ECM

ECM is a new semi-solid slurry preparation method[59–60]. ECM technique begins by pouring the molten alloy into the tilted crucible, where the melt encounters the low-temperature crucible wall and begins to nucleate. Induction heating maintains the temperature of the melt and promotes the growth of the melt in the amorphous manner, ultimately resulting in the semi-solid slurry microstructure. This technique has the advantage of short process, simple structure, and high operability. ECM technique is still in the initial research stage, and there are still some problems to be solved. For example, the grain growth mechanism of semi-solid slurry prepared by ECM technique is not clear.

1.2.9 Gas induction method

Gas-induced superheated-slurry (GISS) process technique was proposed[61–63]. As shown in Fig. 18, argon gas is introduced into the superheated alloy melt through the porous graphite rod. The floating of bubbles in the melt can bring heat out of the melt, the temperature of the superheated alloy melt is decreased to the liquid phase line, resulting in the formation of the primary α-Al crystal nuclei. At the same time, the rupture of gas bubbles in the melt have the stirring effect on the melt. This effect can break up the dendritic microstructure in the melt, and the non-dendritic spherical microstructure is formed. The stirring effect of the gas on the melt in GISS technique is relatively limited, therefore, indicating that this technique can only be used to prepare semi-solid materials with the low solid-phase rate.

Honarmand et al[64] from Iran University of Science and Technology studied the effect of gas-induced semi-solid state machining and addition of Sr on the impact strength and

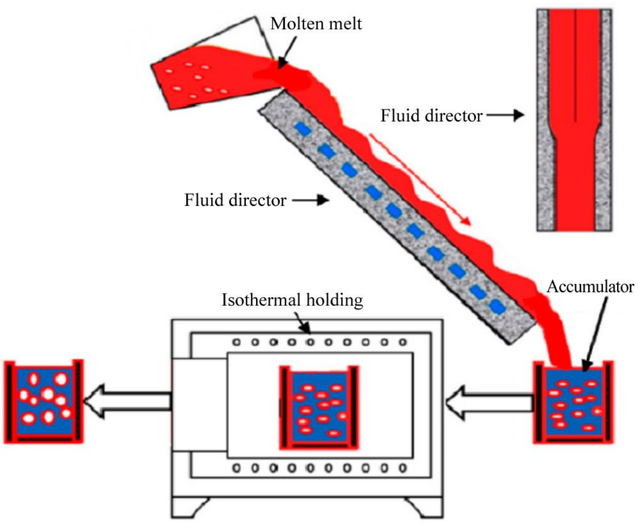

Fig.15 Schematic diagram of SIM technique[55]

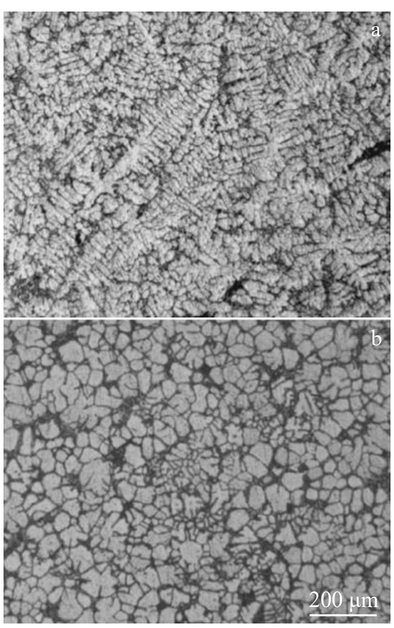

Fig.16 Microstructures of AM60 magnesium alloy prepared by conventional casting (a) and SIM technique (b)[58]

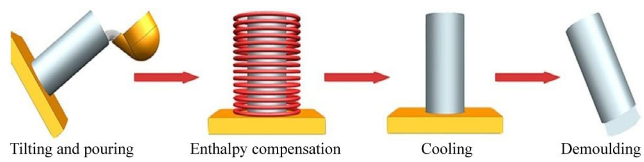

Fig.17 Schematic diagram of ECM technique[60]

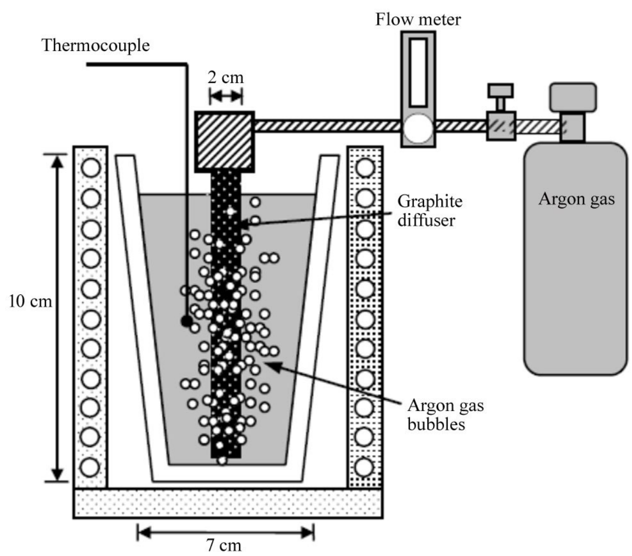

Fig.18 Schematic diagram of GISS technique[61]

microstructure refinement of A380 aluminum alloy. Results show that the use of the GISS technique is effective for preparing semi-solid state microstructure. However, the shape of the primary α-Al grains and the grain size are highly variable. As shown in Fig.19, with the prolongation in time of gas introduction, the size of primary α-Al grains becomes smaller and the shape of the grains is close to spherical.

1.2.10 Ultrasonic vibration method

Since the invention of semi-solid processing technique, researchers expected to introduce ultrasonic vibration into semi-solid pulping technique. Semi-solid slurry prepared by ultrasonic vibration method can be divided into direct ultrasonic vibration (DUV) process and indirect ultrasonic vibration (IUV) process according to different actions of ultrasonic vibration on alloy melt.

The principle of DUV technique is shown in Fig.20. DUV technique includes the variable amplitude rod with ultrasonic vibration in direct contact with the alloy melt, which produces the violent stirring effect on the alloy melt. The dendritic microstructure generated during the crystallization of the melt is broken by the stirring action of ultrasonic vibration. At the same time, the primary α-Al grains are refined, which eventually produce the non-dendritic spheroidal microstructure. Due to the direct action of the variator bar on the alloy melt, secondary contamination of the melt can occur. Meanwhile, the agitation of melt caused by the DUV technique can introduce gases into the melt, resulting in pores in the semi-solid product. Zhang et al[65] prepared semi-solid AZ91 alloy using DUV technique and found that DUV technique can effectively prepare semi-solid slurry. As shown in Fig.21, the semi-solid aluminum alloy prepared at 610 °C has high content of primary α-Al grain and its grain shape is close to spherical.

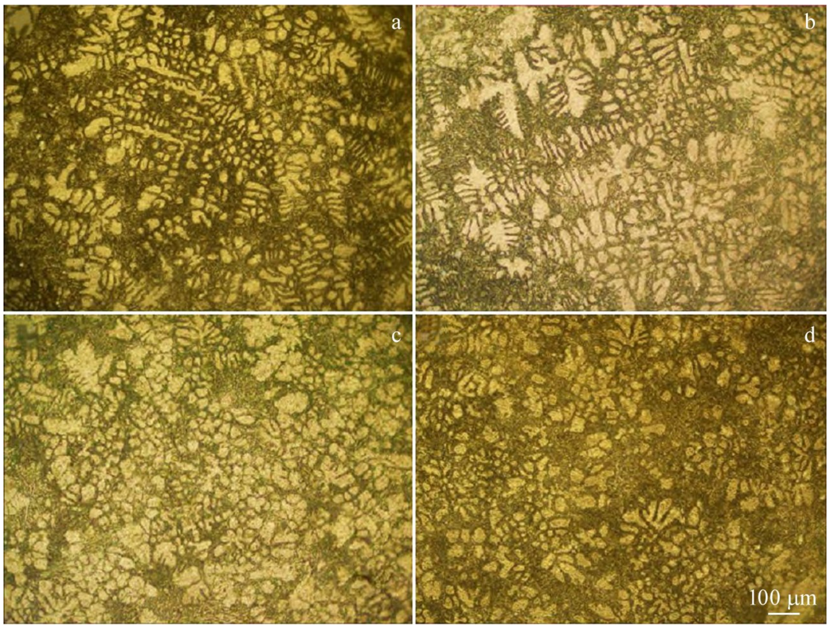

Fig.19 Microstructures of A380 aluminum alloy semi-solid slurry prepared by GISS technique with gas flow rate of 2 L/min, holding temperature of 610 °C, and holding time of 5 s (a), 10 s (b), 15 s (c), and 20 s (d)[64]

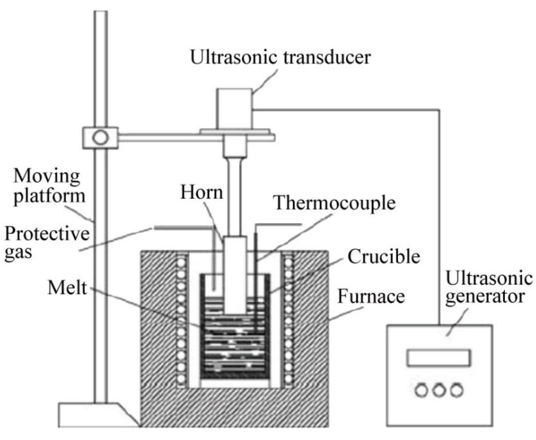

Fig.20 Schematic diagram of DUV technique[65]

The principle of IUV technique is shown in Fig. 22. IUV technique mainly consists of heating furnace, crucible, ultrasonic vibration table, cylinder, etc. IUV technique produces the effect by the vibration of crucible on the alloy melt. The cavitation effect of the melt in IUV technique promotes the nucleation of primary α-Al and causes the primary α-Al grains to grow in the spherical manner, forming amorphous spheroidal microstructure. The melt near the bottom of the crucible has the strong cavitation effect and high content of amorphous globular microstructure. IUV technique causes convection of the melt, which promotes the average distribution of the melt composition in the crucible. But the melt away from the bottom of crucible hardly participates in convection, so there is non-uniformity microstructure in semi-solid slurry prepared by IUV technique. The cavitation effect

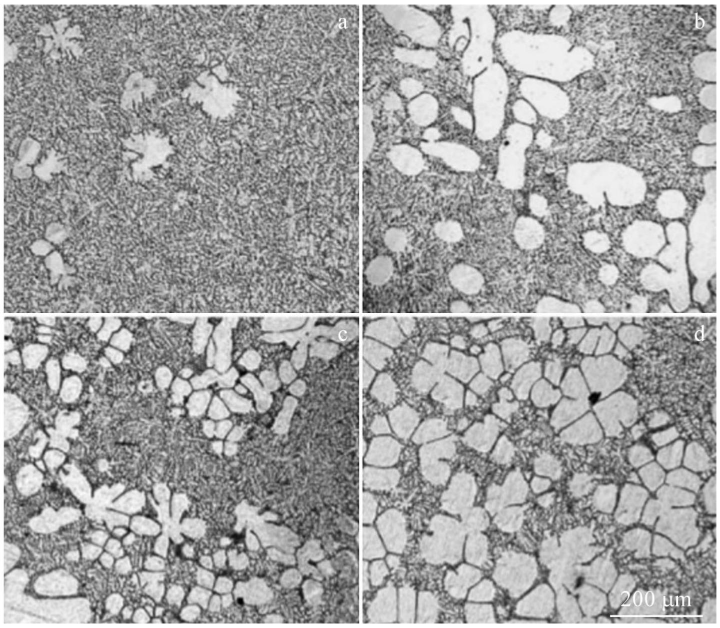

Fig.21 Microstructures of semi-solid AZ91 alloys prepared by DUV technique[65]: (a) 625 °C, (b) 620 °C, (C) 615 °C, and (d) 610 °C

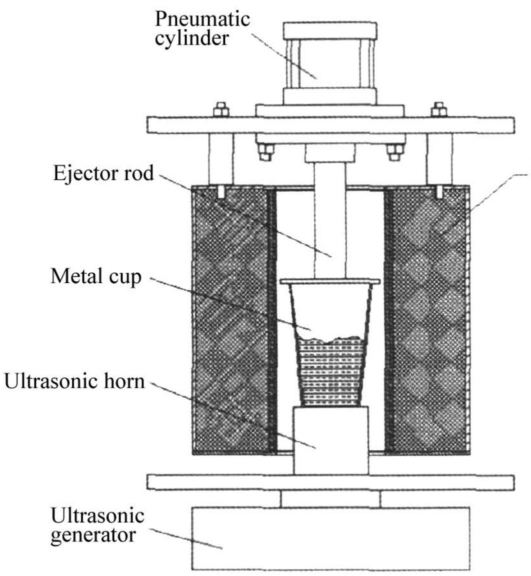

Fig.22 Schematic diagram of IUV technique[68]

of IUV technique eliminates gas bubbles in the alloy melt and increases the density of semi-solid alloys.

Fig.23 shows that the microstructures of as-cast A356 alloy solidified under different squeeze pressures ranging from 25 MPa to 100 MPa. The size of α_1-Al particles decreases with the increase in squeeze pressure, but the change of α_2-Al particles is not obvious.

1.2.11 Mechanical mixing methods

Mechanical mixing method is the first method that has been used to prepare semi-solid slurries[69–71]. Fig. 24 shows the schematic diagram of the mechanical mixing method for preparation of semi-solid slurries. The mechanical mixing method is categorized into continuous mechanical mixing method and discontinuous mechanical mixing method. The continuous mechanical mixing method can be used for semi-solid reforming and industrial production. The discontinuous mechanical mixing method has been replaced by other methods due to low productivity. Direct application of mechanical mixing to the alloy melt can accelerate nucleation of primary α-Al, destroy dendrites, and cause primary α-Al grains to grow in the spherical manner, forming amorphous semi-solid microstructure.

1.2.12 Wave-shaped vibration tilting plate method

The semi-solid slurry preparation technique by wave-shaped vibration tilting plate method was proposed[72–74], and its working principle is shown in Fig. 25. The alloy melt is poured into the tilting plate with wavy surface and vibration is applied to the tilting plate to create conditions for the preparation of semi-solid slurry. The wave-shaped vibrating tilting plate method is an improvement for SEM and NRC methods. The wave-shaped vibration tilting plate method solves the problems of surface bonding and non-uniformity of microstructure due to flat stationary tilting plate.

Semi-solid slurry of AZ91D magnesium alloy was prepared using the wave-shaped vibration tilting plate method, as shown in Fig. 26. It can be seen that semi-solid alloys with homogeneous microstructure, high solid phase ratio, and high shape factor of incipient α-Al grain can be prepared.

1.2.13 Straight pipe method

Yang et al[75–76] from the University of Science and Technology Beijing proposed the straight pipe method, in which the superheated alloy melt is cooled by straight pipe to form semi-solid slurry, and the principle of the straight pipe method is shown in Fig.27. This method is similar to the ICP method and serpentine channel method, in which superheated

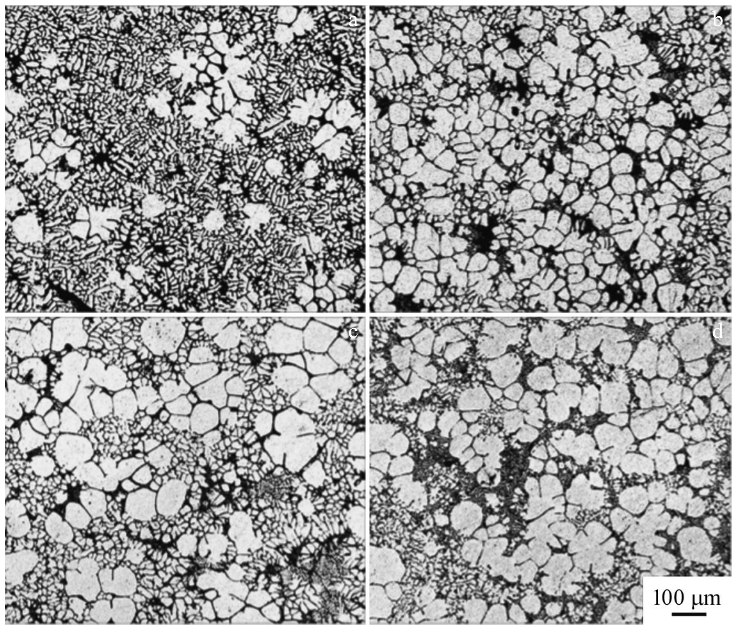

Fig.23 Microstructures of as-cast A356 alloy solidified under different squeeze pressures[66]: (a) 25 MPa, (b) 50 MPa, (c) 75 MPa, and (d) 100 MPa

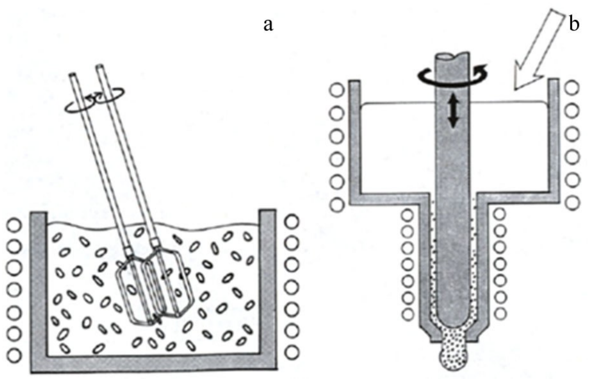

Fig.24 Schematic diagrams of mechanical mixing method[69]: (a) discontinuous mechanical mixing; (b) continuous mechanical mixing

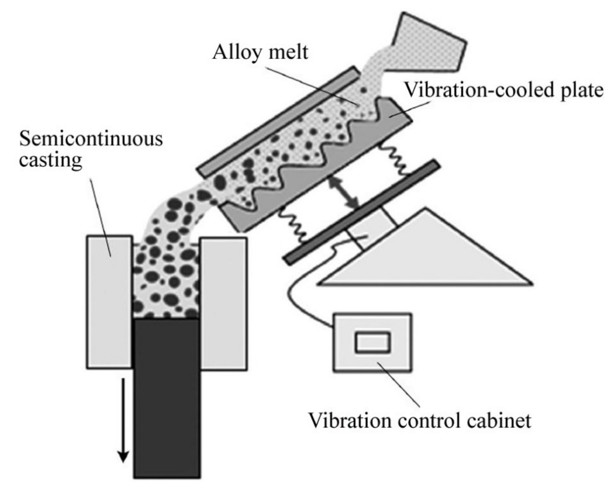

Fig.25 Schematic diagram of wave-shaped vibrating tilted plate method[72]

solid melt flows through the pipe, and the semi-solid slurry is received from the cold pipe wall.

Sun et al[77] from Harbin Institute of Technology applied rotation to the straight pipe and proposed the rotating straight pipe method, and its principle is shown in Fig. 28. Compared with the straight pipe method, the rotating straight pipe method adds the rotational effect to the alloy melt and enhances the generation capability of semi-solid microstructure.

Zhang et al[78] from Dalian University of Technology proposed the damped cooling tube method by adding rotary damping device in the straight tube, and the principle of damped cooling tube method is shown in Fig. 29. In damped cooling pipe method, superheated alloy melt not only receives the cooling effect of the inner wall of the pipe, but also receives the stirring effect of the rotary damping, which further improves the incipient α-Al nucleation capacity and non-dendritic spheroidization capacity.

Finally, the comparison of various semi-solid slurry liquid processing methods is summarized in Table 2.

2 Trends in Semi-solid Slurry Preparation Technique

At present, aluminum alloy semi-solid slurry preparation technique has been gradually applied to various fields with continous development and improvement. The widely used fields include aviation, automobile, rail transportation, electric power, etc. In the future, with the continuous improvement of aluminum alloy semi-solid slurry preparation technique, its application will be more and more extensive, especially

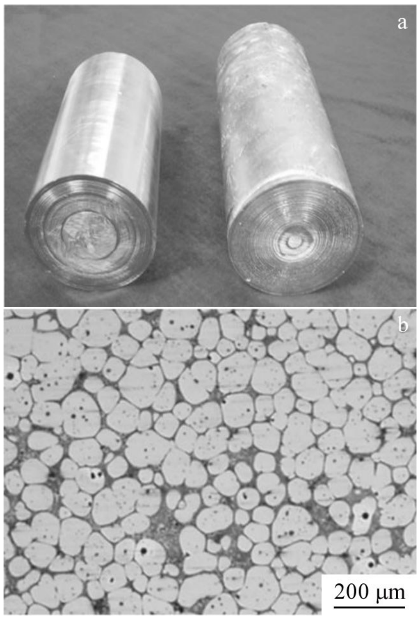

Fig.26 Semi-solid ingot of AZ91D alloy obtained by wave-shaped vibration tilting plate method (a) and its secondary heating microstructure (b)[72]

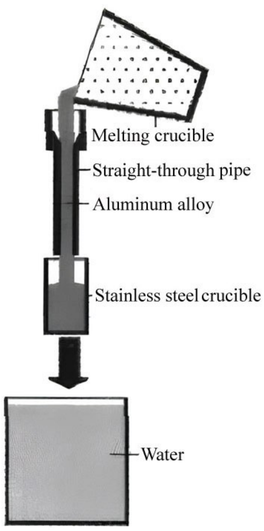

Fig.27 Schematic diagram of straight pipe method[75]

in the field of new energy vehicles and aerospace.

2.1 Problems of aluminum alloy semi-solid slurry preparation technique

Aluminum alloy semi-solid slurry preparation methods are varied, and each has its own characteristics. However, the current technique still relies on a large number of experiences and experiments, and lacks the unified standard specification.

Aluminum alloy semi-solid slurry preparation technique has the high manufacturing cost and needs to be further optimized to reduce cost.

Aluminum alloy semi-solid slurry preparation method with high-quality (uniform microstructure, good spherical effect, high control precision of solid phase rate, no secondary pollution) is lack.

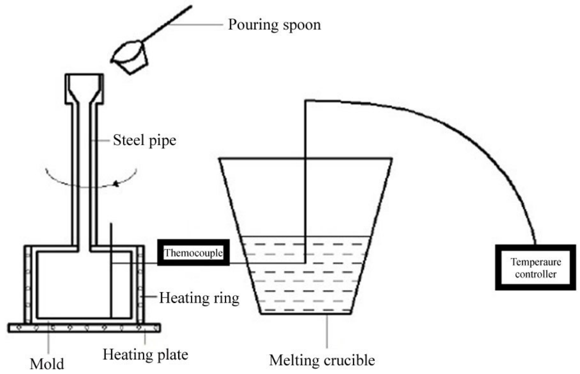

Fig.28 Schematic diagram of rotating straight pipe method[77]

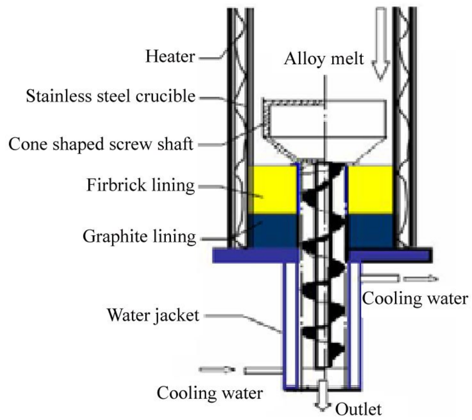

Fig.29 Schematic diagram of damped cooling tube method[78]

2.2 Future development trends of aluminum alloy semi-solid slurry preparation technique

(1) Technical standardization and normalization

Aluminum alloy processing industry associations can formulate unified standard specifications for aluminum alloy semi-solid slurry preparation technique according to the current situation, and give specific requirements and operational specifications for practical semi-solid slurry preparation technique. The formulation of technical standards has a good role in promoting the development, application, and popularization for aluminum alloy semi-solid slurry preparation.

(2) Low cost and high efficiency

Aluminum alloy semi-solid slurry preparation requires special equipment and complex process. Compared with the traditional processing method of aluminum alloy, the cost is high. The semi-solid slurry preparation technique with simple equipment, short process flow, and strong practicality need to be developed, so as to achieve the purpose of cost reduction, and efficiency improvement.

(3) Development of semi-solid compound slurry preparation technique

Aluminum alloy semi-solid slurry preparation methods are varied, but they all have advantages and disadvantages. In the

Table 2 Comparison of various semi-solid slurry liquid processing methods

No.	Semi-solid slurry preparation technique	Advantage	Disadvantage
1	SEED	Low contamination of slurry by the equipment; simple method	High equipment requirements; low slurry preparation efficiency
2	NRC	Accurate control of semi-solid microstructure; strong operability	High equipment requirements
3	TRP	High production efficiency; suitable for semi-solid rheocasting	Uneven distribution of semi-solid micro-structure; secondary contamination
4	LSPSF	High production efficiency, good effect on semi-solid microstructure spheroidization, and uniform distribution of microstructure	High equipment requirements
5	ICP	Simple method; low equipment requirements	Poor spheroidization effect of semi-solid microstructure; uneven microstructure distribution
6	SCP	Simple method; low equipment requirements	Poor spheroidization effect of semi-solid microstructure
7	SIM	Simple operation; low equipment requirements	Average spheroidization effect of semi-solid microstructure; not suitable for semi-solid rheological casting
8	ECM	Simple method; low contamination of slurry by the equipment	Still in initial research stage with unsolved problems
9	GISS	Simple method; low equipment requirements	Low solid phase fraction; low production efficiency
10	DUV/IUV	No pore defects; good effect on semi-solid microstructure spheroidization	High equipment requirements, low production efficiency, and secondary pollution
11	Mechanical mixing method	Simple method; low equipment requirements	Secondary pollution
12	Wave-shaped vibration tilting plate method	Good effect on semi-solid microstructure spheroidization, uniform microstructure distribution, and high solid phase ratio	High equipment requirements
13	Straight pipe method	Simple method; low equipment requirements	Low solid phase ratio; poor spheroidization effect of semi-solid microstructure

future, a variety of semi-solid slurry preparation techniques can be used jointly, making reasonable use of the advantages of each technique to prepare high-quality semi-solid slurry with uniform microstructure, good spheroidization effect, accurate control of solid phase rate, and no secondary pollution.

(4) Development of semi-solid slurry preparation equipment for aluminum alloys protected by vacuum systems or inert gases

Current aluminum alloy semi-solid slurry preparation techniques are mostly operated in open environments, and high-temperature melts of aluminum alloys are oxidized during semi-solid pulping, leading to the decrease in the purity and quality of semi-solid slurries. Therefore, the equipment with vacuum system or inert gas protection to improve the purity and quality of semi-solid slurry needs to be developed.

(5) Software simulation of semi-solid slurry preparation

Currently, there are many semi-solid slurry preparation techniques for aluminum alloys with different principles. Software simulation of the semi-solid slurry preparation process is still a difficult task, and multi-physical field simulation software for semi-solid slurry preparation needs to be developed in the future.

(6) Upgrading automation of semi-solid slurry production

The current semi-solid slurry preparation technique is mostly manually controlled with the low level of automation. In the future, the automation level of semi-solid slurry preparation needs to be improved, which is very helpful for improving the quality of semi-solid slurry and promoting the application and popularization of semi-solid slurry preparation technique.

Briefly, aluminum alloy semi-solid slurry preparation technique is an emerging technique with broad application prospects. In the future, it is necessary to strengthen technical research and application innovation, to further improve the efficiency of this technique and promote it to better serve the manufacturing industry in various fields.

3 Conclusions

Semi-solid slurry preparation technique is one of the key techniques in semi-solid forming of aluminum alloy, which determines the industrial application of semi-solid forming and has the significant impact on the quality of aluminum alloy products. The semi-solid slurry preparation technique of aluminum alloy is summarized, presenting the principles and effects of each semi-solid slurry preparation technique and the mechanism of semi-solid structure formation. Although numerous semi-solid slurry preparation techniques for aluminum alloys have been proposed, some of them still suffer from issues such as poor spheroidization effect, uneven microstructure distribution, secondary pollution caused by slurry preparation equipment, and lack of industrial applications. In the future, it is necessary to further develop semi-solid slurry preparation techniques of aluminum alloys with high quality, high efficiency, low equipment requirements, and wide application in industrial production.

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铝合金半固态浆料制备技术研究现状

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摘　要：半固态成形技术是铝合金铸造成形的一个重要方法，使用半固态成形技术加工的产品具有凝固收缩小、铸件尺寸精度高、成形速度快、生产率高、铸件力学性能好等优点。半固态成形加工的铝合金产品可以进行热处理，且热处理后产品的力学性能接近于钢，但是拥有比钢更轻的质量，在很多领域得到了广泛应用。半固态浆料制备技术是铝合金半固态成形的关键技术之一，决定了半固态成形的产业化应用，同时也对铝合金产品半固态成形质量有很大影响。随着半固态制浆技术的不断发展，铝合金半固态成形技术成为了金属制品加工领域的一项新兴技术。综述了多种铝合金半固态浆料制备技术的原理、特点，比较分析了各种半固态制浆方法的优缺点，并对其未来发展趋势进行了探讨。

关键词：铝合金；半固态成形；半固态浆料制备技术

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