Research progress on squeeze casting in China

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Abstract: Squeeze casting is a technology with short route, high efficiency and precise forming, possessing features of casting and plastic processing. It is widely used to produce high performance metallic structural parts. As energy conservation and environmental protection concerns have risen, lightweight and high performance metal parts are urgently needed, which accelerated the development of squeeze casting technology over the past two decades in China. In this paper, research progress on squeeze casting alloys, typical parts manufacturing and development of squeeze casting equipment in China are introduced. The future trend and development priorities of squeeze casting are discussed.

Key words: squeeze casting; research progress; technology; equipment

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Squeeze casting, also known as liquid forging, is a special casting technique whereby a certain amount of liquid metal is injected into the mold cavity at low speed, then solidified to form castings under pressure. Compared with other casting methods, squeeze casting has a wide range of materials selection, high utilization rate of liquid metal, uniform and dense casting microstructures, excellent mechanical properties, high surface finish and dimensional accuracy. Compared with plastic deformation methods, squeeze casting can make complex parts with lower deformation force and fewer working procedures. In short, squeeze casting is a technology with a short route, high efficiency and precise forming, and possesses the features of both casting and plastic processing. It is widely used in machinery, automobile, household, aerospace and defense industries to produce high performance and high precision parts. The earliest mention of squeeze casting technology was in 1819, but it is generally believed that the publication of the monograph "liquid metal forging", by a Soviet scientist named V. M. Plyatskii, is the sign of the complete establishment of squeeze casting technology[1]. This technology showed rapid development in the 1960s in Europe and North America [1-4]. China began the squeeze casting research in the 1960s and there was a rapid development stage in the 1970s. Since the early 1990s, along with the urgent need for lightweight and high performance products, squeeze casting technology has been of wide concern in China [4].

1 Research on squeeze casting materials

1.1 Aluminum and magnesium alloys

The research of squeeze casting materials has always been an important aspect of squeeze casting technology. The most attention is paid to aluminum alloys and aluminum matrix composites. Magnesium alloys, zinc alloys, copper alloys and iron, including their composite materials, are also involved. Shenyang University of Technology has performed research on the squeeze casting of ZA27, ZA43 zinc alloys and squeeze casting of AZ91D, AM50A magnesium alloys [5-6]. Shanghai Jiaotong University has performed researches on squeeze casting of Mg-Nd (-Zr) magnesium alloys [7]. In zinc alloys, high pressure improves solubility of solute in the matrix and reduces the dendritic segregation due to the refinement and uniform distribution of the eutectic phases. In magnesium alloys, it is found that only lower die and pouring temperatures were favorable to refine grains. When the pouring temperature is above the melting point under pressure, the applied pressure leads to grain coarsening. For the extensively researched aluminum alloys, the industrial application of squeeze casting aluminum alloys is mainly limited to Al-Si alloys which have relatively low mechanical properties [8-10]. Studies have found that high strength aluminum alloys prepared by squeeze casting can achieve excellent mechanical properties, which are close to the level of forging [11]. Based on Al-Cu and Al-Zn series alloys, South China University of Technology has developed a series of high performance squeeze casting aluminum alloys [12-16]: HGZL01 alloy with high strength, high ductility and low thermal crack characteristics; HGZL02 alloy with high strength and fluidity; HGZL03 alloy with high strength, elongation and fluidity; HGZL04 alloy with good castability; HGZL05 alloy with high strength and ductility. Among these, HGZL03 is an Al-Cu-Mn based alloy. Its chemical composition (mass percentage) is 4.5–5.5 Cu, 0.2–0.8 Mn with trace elements of Zr, V, Ti, B and rare earth. This alloy has excellent strength and ductility (as indicated in Fig. 1) under an applied pressure of 75 MPa. The tensile strength in T5 state is 440 MPa and elongation is 20%.

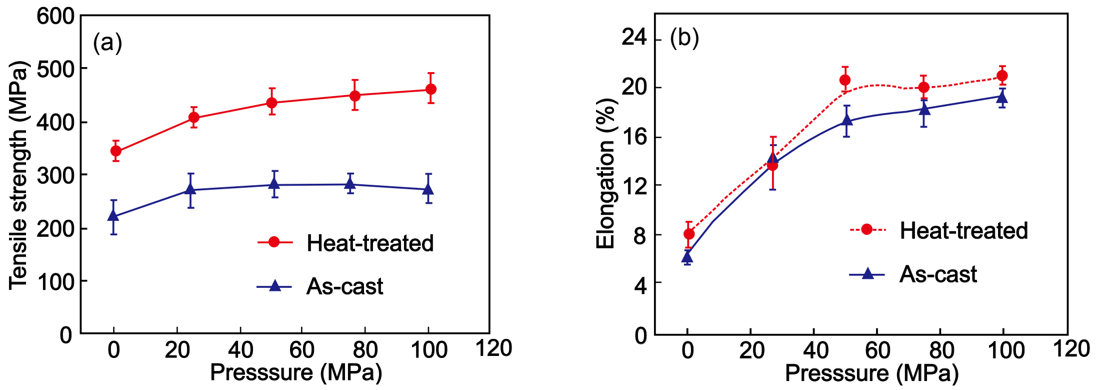


Fig. 1: Tensile strength (a) and elongation (b) of HGZL03 alloy under different applied pressures [13]

Iron is the most harmful impurity element and often difficult to avoid in aluminum alloys. Moreover, it will accumulate during the recycling of aluminum scrap. In industrial production, iron content is often strictly controlled in high performance aluminum alloys. For instance, in American A206.2 alloy, iron content is controlled below 0.07wt.%, and in Chinese ZL205A alloy, iron content is controlled under 0.15wt.%. Therefore, in the preparation of high performance aluminum alloys, the requirements for raw materials and melting practice are very strict. In order to realize energy saving, emission reduction and resources recycling in aluminum alloy production, relaxing the iron content limit in aluminum alloys is a very meaningful endeavor. In the process of developing high performance aluminum alloys, South China University of Technology efficiently combined the squeeze casting process with modification treatment of iron-rich phases. With Al-Cu-Mn alloy as the object, the solidification behavior of iron-rich phases and its effect on mechanical properties of the alloy were systematically studied. It was found that the squeeze casting process can increase the maximum iron content limit in aluminum alloys [17-19]. For example, under the T5 heat-treated condition, the tensile strength and the elongation of Al-5.0Cu-5.0Mn alloy with 0.5wt.% Fe prepared by squeeze casting under a pressure of 75 MPa are 395 MPa and 14%, respectively. Compared with gravity die casting, these are increased by 30% and 140%, respectively. In the squeeze casting process, needle-like β-Fe (Al_7Cu_2Fe) can completely transform into Chinese-script α-Fe (CuFe). At the same time, the number and the size of iron-rich phases can be significantly reduced. In addition, the squeeze casting process enhances the cooling rate and reduces casting defects such as shrinkage. All these are important indications of the significantly improved performance of the aluminum alloys (as indicated in Fig. 2).

1.2 Metal matrix composites

Squeeze casting is particularly suitable for the preparation and forming of continuous and discontinuous ceramics reinforced metal matrix composites. This is because the technology

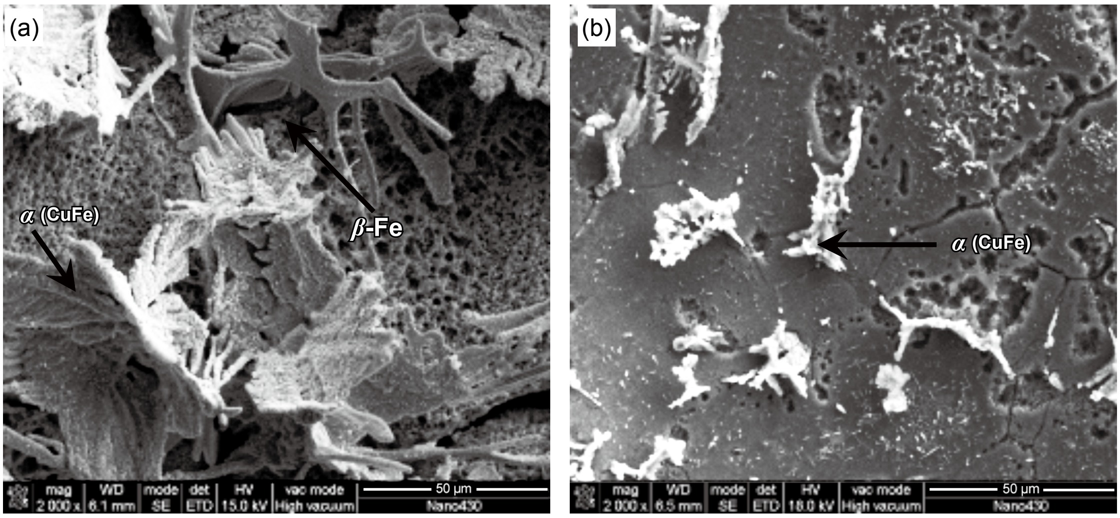


Fig. 2: Microstructures of Al-5.0Cu-0.6Mn-0.5Fe alloy under pressures of 0 MPa (a) and 75 MPa (b) [19]

has the following advantages: (1) It can improve the fluidity of the melt, creating favorable conditions for the filling of reinforcement gaps to obtain cast structure without voids; (2) The contact time between molten metal and reinforcement is short, which can slow down the interfacial reaction and improve the interfacial bonding status; (3) Material design has a large range of choice: aluminum, magnesium, zinc, copper alloys, etc. can all be used as matrix materials. As for the reinforcements, continuous fiber, whisker, particles, porous and layered materials, etc. can be used. Because of the above advantages, squeeze cast metal matrix composites become one of the important research fields. Many universities and institutes in China have carried out research on squeeze cast metal matrix composites. For example, pressure infiltration casting of aluminum matrix composites was adopted in Southeast University. The reinforcements were alumina short fibers (δ) and aluminosilicate short fiber (high-alumina), the matrices were ZL108 and ZL109 [20]. Qu Shoujiang et al. [21] of Harbin Institute of Technology adopted two-stage squeeze casting technology: low pressure permeating and high pressure solidification, to prepare 25vol.% SiC_p/Al composite materials, further improving its strength and ductility by hot extrusion. Zhu Dezhi et al [22] of South China University of Technology, prepared hybrid enhanced C_f/LF6 aluminum matrix composites by the squeeze casting process. Its microstructure is shown in Fig. 3. In addition, the squeeze casting process was used to prepare Si_3N_4 particles-reinforced 2024 aluminum alloy and Ti fiber-reinforced Al-6Mg composite material. Its performance and microstructural evolution were also studied [23, 24]. Squeeze casting metal matrix composites have been applied in aerospace, transportation, defense equipment and other fields globally; however, the industry and the enterprise standard on metal matrix composites has not been well established yet in China, and they are only used in some special fields, such as national defense [25].

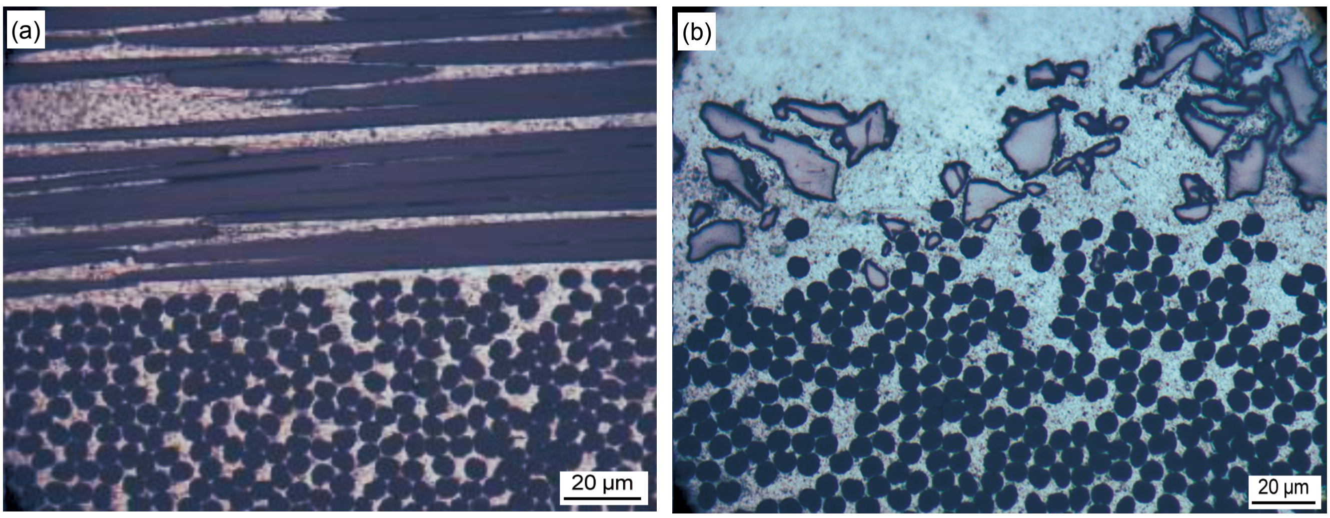


Fig. 3: Microstructures of hybrid enhanced C_f/LF6 aluminum matrix composites prepared by squeeze casting: C_f/LF6 aluminum matrix composites (a); C_f+SiC_p/LF6 aluminum matrix composites (b) [22]

2 Research on squeeze casting process and typical parts

2.1 Squeeze casting process and its numerical simulation

The optimization of processing parameters is one of the major branches of squeeze casting, which usually focuses on the effect of the parameters such as dwelling time, squeeze pressure, pouring temperature and die temperature on alloys' properties, microstructure and casting defects. The study mainly consists of: analysis of specific parameters based on experiment; optimization of parameters with applying statistic methods on experimental data; calculation of squeeze pressure and dwelling time with theory or empirical study, especially in direct squeeze casting [26]. For example, the study on solidification of Al-Si-Cu alloys with different applied pressures has shown that, according to experimental results and Sieverts' Law calculations, applied pressure of 25 MPa can make the hydrogen solubility in solid phase exceed the initial hydrogen content in liquid and hence prevent the formation of gas porosity [27]. The investigation on the casting-die interfacial heat transfer behavior indicated that the change of interfacial heat transfer coefficients includes increase at gravity solidification, dramatic increase, slow decrease and stable periods in squeeze casting condition, while it only consists of increase, decrease and stable periods in gravity casting condition. Squeeze pressure can decrease the interfacial gap and 50 MPa is a peak pressure for elimination of the gap [28].

Numerical simulation is one of the important tools for optimizing squeeze casting process, which has been paid great attention. Han [29-30] established a finite element model coupling the heat transfer and stress to describe the temperature and stress fields during solidification of squeeze casting. In the model, enthalpy was used to treat latent heat and a thermal visco-elastic-plastic model was set for the solidified shells and liquid metal. Also volumetric shrinkage was considered and the pressure, air gap and radiation were counted in the interfacial heat transfer. Through mathematical modeling,

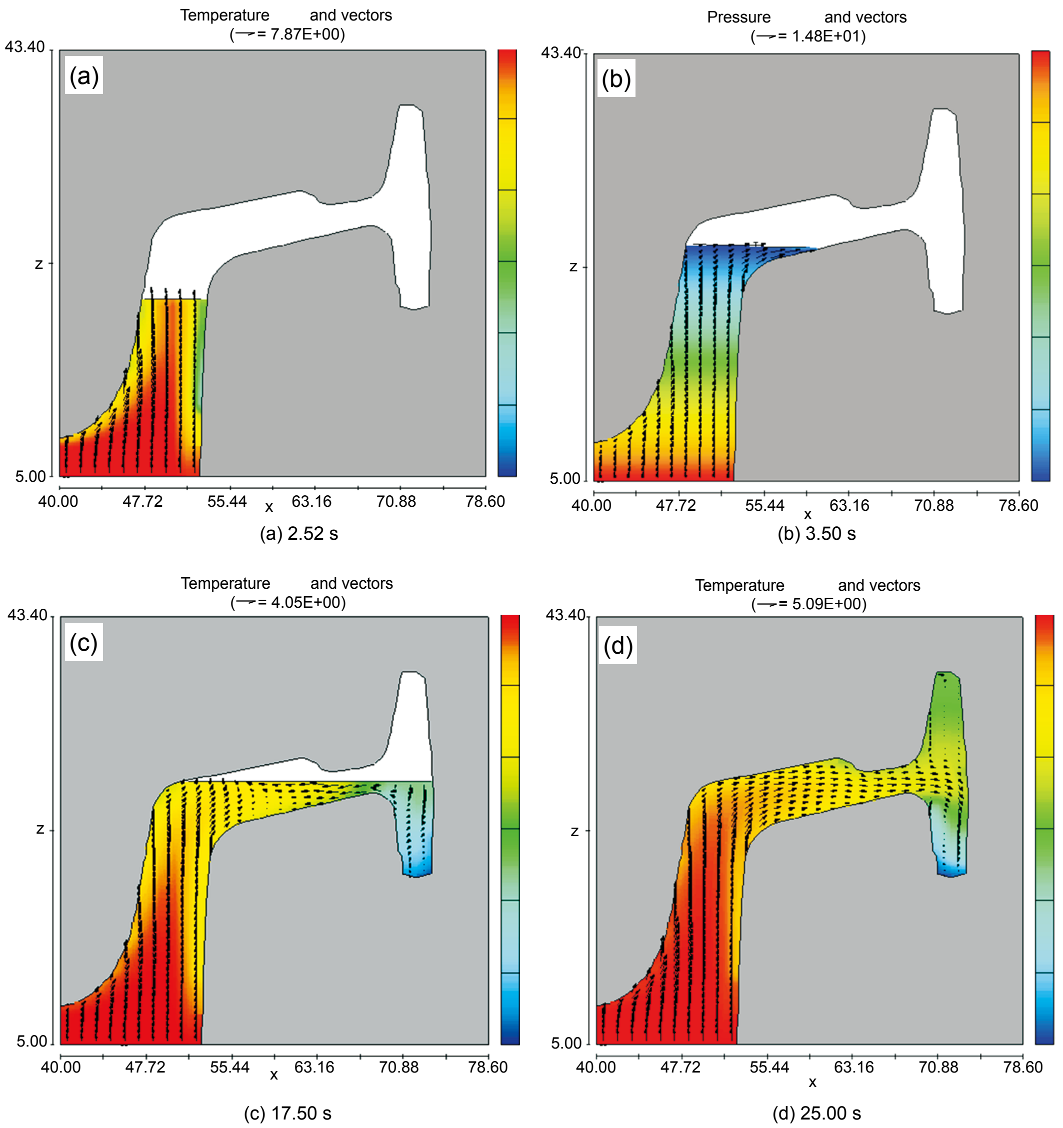


Fig. 4: Simulation of filling behavior for in-direction squeeze casting wheel by multi-stage injection [34]

Ma [31] studied temperature fields of the cylindrical shaped squeeze castings and calculated the solidification shrinkage and volume of shrinkage cavity. Based on two dimensional cylindrical coordinate systems, Wang [32] established the model of temperature fields in squeeze casting with different finite element methods. With a similar system, San [33] simulated the temperature distribution of ZA27 squeeze casting with large height-radius ratio.

To analyze filling behavior and choose injection parameters for the wheel squeeze casting process, Li Y Y et al [34] carried out simulation on the filling and solidification process by considering the turbulence, heat transfer and friction of the die wall. Optimized multi-stage injection was proposed to avoid entrapment of gas and oxides. Simulation results shown in Fig. 4 indicate that in the first stage, the liquid melt flowing steadily though the injection increased in velocity, and the energy lost and temperature decrease of the liquid melt were reduced due to the less contact time between the melt and the die [Fig. 4(a)]. In the second stage, flow velocities in the vicinity of the free surface were reduced and turbulent flow was not found there [Fig. 4(b)]. In the last stage, the liquid melt moved upwards steadily [Fig. 4(c)]. The simulation results showed that with modified injection, the filling time and turbulent flow were reduced, and at the end of the filling, the minimum temperature in the rim was 904 K, which was higher than that of the constant velocity injection. This meant the solidification during the filling was reduced. At the end of the filling, the decreasing temperature distribution from hub to spoke and rim was favorable to the transfer of exerted pressure on the solidifying casting [Fig. 4(d)].

2.2 Typical squeeze casting parts

Squeeze casting is an important method for producing high requirement components in mechanical, automotive, electric, aerospace, and national defense industries. The largest wheels of 30 kg in weight or 580 mm in dimension with a tensile strength of 350–390 MPa and elongation of 5%–12% were prepared by squeeze castings in Ningbo Branch of Ordnance Science Institute of China[35]. The squeeze castings of automotive instruments, such as steering valves and auto-bike frames with 2A01 alloys were also reported [35]. The ZL108 aluminum alloy automotive brake pump with the tensile strength of 290 MPa, elongation of 1.6% and hardness of HB105 was fabricated using squeeze casting method in Wuhan University of Science and Technology [36]. By heating closed filling channels and using quantitative pouring, squeeze casting of Mg alloy wheel was produced in Chongqing University [37]. The squeeze casting of ferrous metal alloys was developed in Beijing Jiaotong University [38, 39] for components in charcoal mine and railway industries such as hydraulic valve bodies and breaking machine punches. As for metal matrix composites, squeeze casting process is appropriate for making complex components and displays the characteractics of low-cost, time-saving and mass production. Luo[40] proposed a method that combines squeeze casting and hot extrusion methods. Liquid metal was first infiltrated into a ceramic preform and then hot extrusion was applied on the composites. The local reinforced pistons were produced by squeeze casting with pressure infiltration and have been used in several models of automotive engines [20].

The study of large complex components prepared by squeeze casting was also carried out in South China University of Technology. Figure 5 shows photographs of a squeeze cast wheel with a diameter of 670 mm and a transmission supporting frame with a project area of 580 mm × 480 mm. In the study, the developed HGZL03 aluminum alloy was used. Inspection of the wheel casting showed that gas pores and shrinkage defects were absent. The as-cast micrograph of the samples taken from different parts of the wheel showed denser and finer grain microstructures than those in the gravity cast Al-Cu alloy. Specimens were cut from the hub, spoke, and rim of the T5 heat-treated wheels. The measured ultimate tensile strength and elongation of the specimens were 350–390 MPa and 7%–9.5%, respectively [41-42].

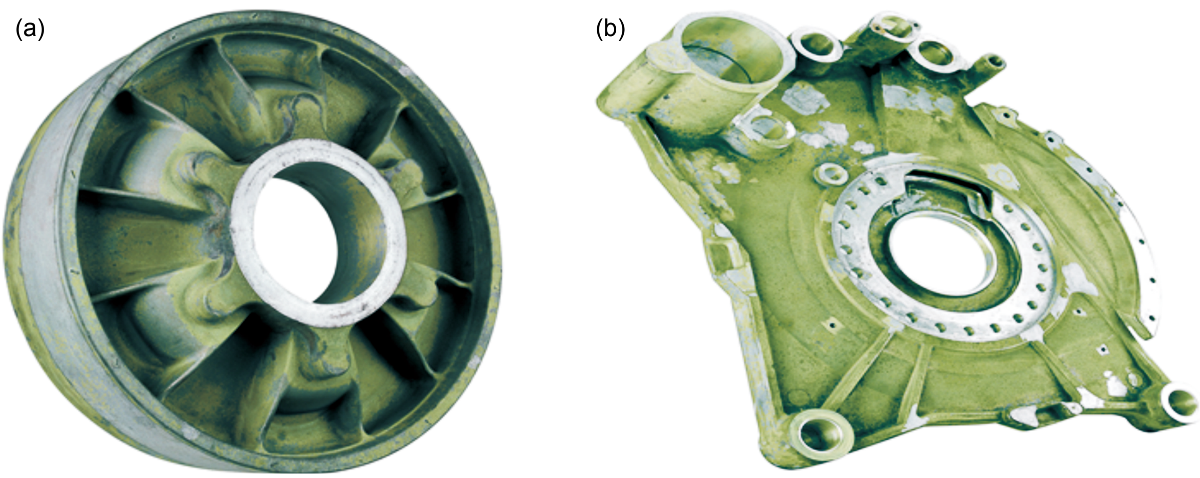


Fig. 5: Squeeze casting wheel (a) and transmission supporting frame (b) [41-42]

3 Research on squeeze casting equipment

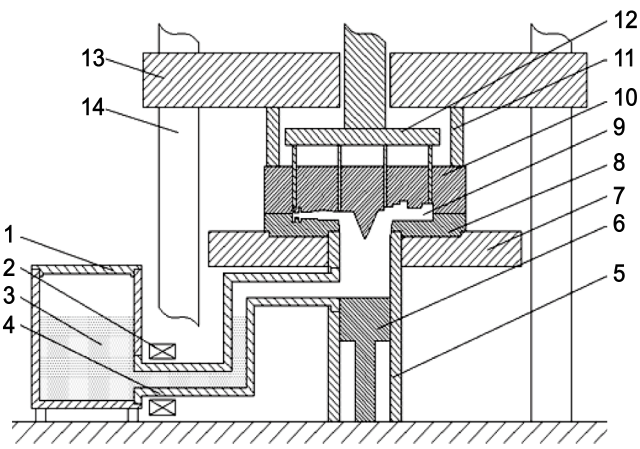
Traditional squeeze casting equipment in China was generally refitted from hydraulic press. It turns out to be of single species, short of functions, poor performing parameters and low production efficiency. Currently, there are approximately 200 squeeze casting machines in China, of which about 80% are refitted ones. Most special squeeze casting machines are imported, which cannot produce large complex parts because of the low clamping force. In recent years, research of squeeze casting equipment has made significant progress in China, mainly as follows:

(1) Seriation and large-size squeeze casting equipment

South China University of Technology and Keda Clean Energy Co., Ltd. developed a large squeeze casting equipment with the world's largest 40,000 kN clamping force, which can be used to produce large and complex aluminum alloy parts. The manufacture of the equipment was completed, and will be put into production soon after installation and commissioning. In addition, 2,500 kN horizontal and 33,000 kN vertical squeeze casting machines were also developed. Suzhou Sanji Foundry Equipment Co., Ltd. has developed a series of squeeze casting machines, including SCH-350A 3,500 kN horizontal machine, SCV-800A full vertical machine, 8,000 kN, MLC-1000 10,000 kN horizontal light alloy casting machine and SCV-2000 20,000 kN full vertical machine[35]. The Y28 vertical squeeze casting machines developed by Foshan Shunde Huada Machinery Co., Ltd., has three sizes, the clamping force of which are 550 kN, 800 kN, 1500 kN respectively. Based on common crank presses, Chiu Ta Hydraulic Machine MFG. Co., Ltd. developed six kinds of vertical squeeze casting machine series, the clamping forces of which are 1500 kN, 2000 kN, 2500 kN, 5000 kN, 8000 kN and 12000 kN, respectively [43].

(2) Equipment for novel squeeze casting process

In order to avoid the filling insufficiency of the parts in the location far away from punch, laminated pouring and accumulated liquid forging technology has been put forward in a modified squeeze casting machine by Luo Shoujing et al. [44] from Harbin Institute of Technology. Li Yuanyuan et al. [45] proposed an indirect squeeze casting method using electromagnetic force filling (shown in Fig. 6). In this method, melt can be forced by the electromagnetic pump to flow from the transmission pipeline passing the die chamber to fill the mold cavity. When aluminum melt was transferred in a hermetic space, better melt quality can be naturally guaranteed. Furthermore, a closed-mold pouring and direct squeeze casting technique was proposed [46]. In this method, an additional space is provided to the upper die to implement a bidirectional squeeze on aluminum alloy melt between the upper die punch and the squeeze punch during the alloy solidification. As a result, the density and uniformity of the castings will be improved. Additionally, complex squeeze casting technology combined with direct and indirect squeeze casting features, and semi-solid squeeze casting technology for aluminum alloy and magnesium alloy are also under development [35].



1 - Holding furnace; 2 - Electromagnetic pump; 3 – Melt; 4 - Transmission pipeline; 5 - Die chamber; 6 - Squeeze punch; 7 - Fixed die plate; 8 - Fixed die; 9 - Die cavity; 10 - Upper die; 11 - Upper die bearer; 12 - Ejector system; 13 - Moving die plate; 14 - Casting machine tie bar

Fig. 6: Electromagnetic force indirect filling squeeze casting [45]

(3) Design theory of squeeze casting equipment

In the aspect of general system design in squeeze casting equipment, from the view of system engineering, South China University of Technology proposed a general structure of squeeze casting forming system after discussing the general functions and the information architecture of this forming system. Furthermore, the axiomatic design theory was introduced to guide the equipment design and the method for functional decomposition design of axiomatic design based on connections is presented to actively avoid functional coupling of axiomatic design. Based on this design theory, the axiomatic design framework was established to perform the general design of 2,500 kN and 40,000 kN squeeze casting equipment. A components design sequence based on the decomposition design of the equipments' main function was developed. Accordingly, the design efficiency and quality for squeeze casting equipment were improved[47]. Moreover, a method of estimating equipment performance from the view of logistics was proposed. A logistics performance evaluation system of squeeze casting equipment was built and simulated using Flexsim software. The results revealed the relationship between the utilization of the equipment's main mechanisms and the production cycle time. In addition, considering the characteristics of melt hermetic transmission and die pre-close, general design of complex squeeze casting equipment and logistics simulation were conducted [48].

4 Outlooks

As the development of metal structures moves toward large-size, complexity, high-performance and lightweight, squeeze casting technology will have great application potential. For example, the production of aluminum wheels in the automobile industry reached more than 200 million in 2010, among them, more than 99 million were produced in China. Squeeze casting process has a huge market. However, there are serious challenges we have to face. The following studies need to be carried out in the near future:

(1) Based on the need for improving material performance and forming of special parts, extra attention should be paid to indirect squeeze casting by analyzing the physical metallurgy behavior and force transmission during liquid metal solidification under pressure. Aimed at precision forming of large complex parts by squeeze casting, development of new materials with better comprehensive performance is demanded.

(2) The solidification conditions of large complex parts by squeeze casting are complicated. Research should focus on process optimization to achieve uniform microstructure and mechanical properties. Reliable prediction and accurate control of casting defects are of great significance. The manufacturing cycle of large casting mold is long and the cost is expensive. The advanced numerical simulation technique should be developed and applied as an important means to optimize the mold design.

(3) High efficiency and high precision squeeze casting equipment is important to guarantee the efficiency and precision forming of squeeze casting parts. Researchers should focus on broadening adaptability, studying novel large-tonnage clamping mechanism, adopting advanced control technology, etc., to develop advanced squeeze casting equipment.

In conclusion, squeeze casting technology can greatly improve the performance of aluminum alloys and other light alloys; promote the utilization of aluminum alloys instead of steel; reduce the weight of automobile, machinery equipment and military equipment; promote energy conservation and environmental protection. What's more, squeeze casting technology can realize efficient near-net-shape forming of large and complex castings, which is greatly beneficial to achieve energy saving, material saving and cost reduction. Finally, squeeze casting technology can greatly lessen the impurity restriction in raw material, which is advantageous to realize the recycling of waste materials such as aluminum scrap, so as to promote sustainable development.

5 Conclusions

Due to the rapidly increasing demand for lightweight and high performance metal parts, significant progress in squeeze casting has been made in China in the past two decades. The main emphasis of development of advanced squeeze casting materials is on Al- and Mg-based alloys, and their composites. The research of the squeeze casting process and parts forming include the optimization of the squeeze casting process and its numerical simulation, and the manufacture of large complex light-weighted parts. As for the research of squeeze casting equipment, the main concern focuses on the development of serialized advanced equipment with high efficiency and high precision.

References

[1] Plyatskii V M. Liquid Metal Forging. Moscow: Mashinostroenie,1964. (In Russian)

[2] Chadwick G A, Yue T M. Principles and application of squeeze casting. Metals and Materials, 1989, 5(1): 6–12.

[3] Ghomashchi M R, Vikhrov A. Squeeze casting: an overview. Mater. Process Technol., 2000, 101: 1–9.

[4] Qi P X. Squeeze casting technology geared to the 21st century. Special Casting and Nonferrous Alloys, 2002 (Die Casting Special): 209–213. (In Chinese)

[5] Li R D. Non-equilibrium solidified ZA43 alloy organization under high pressure. Special Casting and Nonferrous Alloys, 2003(6): 16–17. (In Chinese)

[6] Yu H P. Research of microstructure and mechanical properties of squeeze casting AZ9ID and AM50A. Special Casting and Nonferrous Alloys, 2003 (Die Casting Special): 198–199. (In Chinese)

[7] Yang Y L, Peng L M, Fu P H, et al. Effects of process parameters on the macrostructure of squeeze-cast Mg-2.5%wt%Nd alloy. Materials Transactions, 2009, 50(12): 2820–2825.

[8] Maleki A, Niroumand B, Shafyei A. Effects of squeeze casting parameters on density, macrostructure and hardness of LM13 alloy. Materials Science and Engineering, 2006, A428: 135–140.

[9] Chen Z W, Thorpe W R. The effect of squeeze casting pressure and iron content on the impact energy of A1-7Si-0.7Mg alloy. Materials Science and Engineering, 1996, A221: 143–153.

[10] Lee J I, Han Y S, Lee H I, et al. Microstructures and mechanical properties of squeeze cast Al-Si-Cu-Mg alloy. Korean Inst. Met. Mater, 1994, 32(10): 1259–1268.

[11] Yue T M. Squeeze casting of high-strength aluminum wrought alloy AA7010. Journal of Materials Processing Technology, 1997, 66: 179–185.

[12] Li Y Y, Guo G W, Zhang W W, et al. A casting aluminum alloy with high strength and ductility and thermal crack tendency: China, ZL01127654.1, 2002. (In Chinese)

[13] Zhang W W, Li Y Y, Zhu Q L, et al. A squeeze casting aluminum alloy with high strength and ductility: China, ZL200510037105.5, 2006. (In Chinese)

[14] Li Y Y, Zhang M, Zhang W W, et al. A direct squeeze casting high strength aluminum alloy: China, ZL200510037104.0, 2006. (In Chinese)

[15] Zhao H D, Zhang K W, Li Y Y, et al. A squeeze casting al-si-cu alloy: China, ZL200810199018.3, 2009. (In Chinese)

[16] Zhang W W, Zhang D T, Zhao H D, et al. A Squeeze casting Al-Zn alloy with high strength and ductility: China, ZL201110375252.9, 2012. (In Chinese)

[17] Zhang W W, Lin B, Zhang D T, et al. Microstructures and mechanical properties of squeeze cast Al-5.0Cu-0.6Mn alloys with different Fe content. Materials and Design, 2013, 52: 225–233.

[18] Zhang W W, Lin B, Fan J L, et al. Microstructures and mechanical properties of heat-treated Al-5.0Cu-0.5Fe squeeze cast alloys with different Mn/Fe ratio. Materials Science and Engineering A, 2013(588): 366–375.

[19] Lin B, Zhang W W, Lou Z H, et al. Comparative study on microstructures and mechanical properties of the heat-treated Al-5.0Cu-0.6Mn-xFe alloys prepared by gravity die casting and squeeze casting. Materials and Design, 2014, 59: 10–18.

[20] Wu S Q. Application of ceramic short fiber reinforced al alloy matrix composite to piston of internal combustion engines. Special Casting and Nonferrous Alloys, 2003 (Die Casting

Special): 18-19. (In Chinese)
[21] Qu S J, Geng L, Cao G J, et al. Microstructure and properties of deformable sicp/al composite fabricated by squeeze casting method. Acta Materiae Compositae Sinica, 2003, 20(3): 69–73. (In Chinese)
[22] Zhu D Z, Chen W P, Zhao H D, et al. The organization and impact performance of fiber reinforced aluminum matrix composites prepared by squeeze casting. In: Proc. China Foundry Week 2012, Suzhou, China, 2012: 530–534. (In Chinese)
[23] Xiu Z Y, Yang W S, Chen G Q, et al. Microstructure and tensile properties of Si_3N_{4p}/2024Al composite fabricated by pressure infiltration method. Materials and Design, 2012, 33: 350–355.
[24] Zhu D Z, Chen G Q, Wu G. H, et al. Hypervelocity impact damage to Ti-6Al-4V meshes reinforced Al-6Mg alloy matrix composites. Materials Science and Engineering A, 2009, 500: 43–46.
[25] Zhang D, Zhang G D, Li Z Q. The Current State and Trend of Metal Matrix Composites. Materials China, 2010, 29(4): 1–7. (In Chinese)
[26] Zhang W W, Zhao H D, Zhang D T, et al. Progress in technology of squeeze casting for metal materials. Materials China, 2011, 30(7): 24–32. (In Chinese)
[27] Zhang K W, Zhao H D, Ouyang X X, et al. Microstructure and mechanical properties of Al-Si-Cu-T4 solidified at different squeeze pressures. The Chinese Journal of Nonferrous Metals, 2009, 19(4): 625–632. (In Chinese)
[28] Li J W. Experiment analysis and numerical modeling of thermo-mechanical behavior in aluminum squeeze casting. Dissertation, South China University of Technology, 2014. (In Chinese)
[29] Han Z Q, Zhu W, Liu B C. Therm-mechanical modeling of solidification process of squeeze casting Ⅰ. Mathematic Model and Solution Methodology. Acta Metallurgica Sinica, 2009, 45(3): 356–362. (In Chinese)
[30] Zhu W, Han Z Q, Liu B C. Therm-mechanical modeling of solidification process of squeeze casting Ⅱ. Numerical Simulation and Experimental Validation. Acta Metallurgica Sinica, 2009, 45(3): 363–368. (In Chinese)
[31] Ma J, Meng D Y, Chen W S. Computer simulation of high chromium cast iron of squeeze casting. Journal of Hebei University of Science and Technology, 2002, 63(4): 63–66. (In Chinese)
[32] Wang Z, Huo W C, Zhang J S. The computer simulation and verification of solidification process of liquid die forging. Ordnance Material Science and Engineering, 1988(2): 14–20. (In Chinese)
[33] San J C. Digital simulation of squeeze casting of za27 alloy with large ratio of height to diameter. Dissertation, Shenyang University of Technology, 2006. (In Chinese)
[34] Li Y Y, Zhang M, et al. Study on fabrication of a large Al-Cu-Mn wheel with indirect squeeze casting process. Materials Science Forum, 2006, 532–533: 353–356
[35] Qi P X. The latest development of squeeze casting technology. Special Casting and Nonferrous Alloys, 2007, 27(9): 688–694. (In Chinese)
[36] Luo J X, Hu J H. Research and application of squeeze cast brake pump for automobile. Foundry, 2002, 4: 214–217. (In Chinese)
[37] Wu Z C, Long S Y. A New Squeeze casting process for magnesium wheels production. Foundry, 2005, 54(9): 878–880. (In Chinese)
[38] Xing S M, Zhang M L, Xing W B. Squeeze casting for valve bodies. Foundry, 2008, 57(2): 137–139. (In Chinese)
[39] Wu X L, Xing S M, Yao S Q, et al. The design of squeeze casting process and mould of crusher hammers. Special Casting & Nonferrous Alloys, 2007, 27(11): 858–860. (In Chinese)
[40] Luo S J. Liquid extrusion of composites. Press of Metallurgy Industry, Beijing, 2002. (In Chinese)
[41] Li Y Y, Hu Y, Zhao H D, et al. Vertical indirect squeeze casting process of an al-cu-mn alloy frame part. Materials Science Forum, 2009, 628–629: 605–610.
[42] Li Y Y, Zhang M, Zhao H D, et al. Study on fabrication of a large al-cu-mn wheel with indirect squeeze casting process. Materials Science Forum, 2006, 532–533: 353–356.
[43] Qi P X. The present situation and the development of squeeze casting machine in China. Special Casting and Nonferrous Alloys, 2010, 30(4): 305–308. (In Chinese)
[44] Luo S J, Jiang C F, Sun Y. Liquid die forging and laminated manufacturing technology. Chinese Journal of Mechanical Engineering, 2005, 16(7): 634–635. (In Chinese)
[45] Li Y Y, Zhao H D, Shao M, et al. A filling method and its device of indirect squeeze casting using electromagnetic: China, 200910041401.0, 2009.07.21. (In Chinese)
[46] Zhang W, Min H N, Qiu C, et al. A closed mold filling method and its device of direct squeeze casting: China, ZL201210194868.0, 2012. (In Chinese)
[47] Deng J X, Shao M. Method for functional design of axiomatic design based on connections. Chinese Journal of Mechanical Engineering, 2011, 24(3): 364–371. (In Chinese)
[48] Min H N, Shao M, Zhang W. Composite squeeze casting of large parts. Applied Mechanics and Materials, 2013, 319: 369–372.

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