Overview of Injection Molding Technology for Processing Polymers and Their Composites

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Abstract

Injection molding technology has been in development for almost 150 years. Injection molding is a molding technology that melts the material with the aid of a screw and an external heating device and then injects it into a mold to form the corresponding product as the mold cools. At present, many types of materials can be used to mold products by injection molding. Many requirements and problems in the processing of different materials have also caused the birth of many molding processes. At present, injection molding has been applied in many fields, from daily necessities that are closely related to our lives to parts and components in the aerospace field. At present, injection molding still faces the challenges of processing new materials, and the continuous improvement of the existing equipment technology is required for the continuous development of injection molding.

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1. Introduction

Injection molding technology is one of the main methods of industrial processing. Most injection machines used in industry today are screw-type injection machines. According to the driving mode, injection machines are mainly divided into electric injection machines and hydraulic injection machines.^[1-3] It is a powerful molding method that can mold plastic products of various shapes and sizes. It is also the preferred process for products with complex three-dimensional structures. From micron gears,^[4-6] micron needles,^[7-9] etc. to plastic bottles, plastic barrels and daily necessities that are common in daily life, they can be molded by injection molding. Injection molding technology can be used for a variety of materials, including composite materials, foamed materials, thermoplastic and thermosetting

plastics and rubber, etc.^[10-17] There are also various forms of injection molding such as gas-assisted molding, water-assisted molding, micro-injection molding, injection foam molding, low-pressure molding, injection compression molding, etc.^[18-29]

The process of injection molding mainly includes three stages: three processes of filling, filling and holding. During the plasticizing stage of the injection process, the screw conveys the plasticized material forward at a certain speed. As the screw groove of the screw becomes shallower, the material is compacted and continuously conveyed forward. The head is continuously accumulating, waiting for the arrival of the injection instruction, and at the same time, the screw will continuously retreat as the back pressure of the injection machine increases during the injection process. When the injection is started, the screw moves forward, and the material continuously fills the mold. At the same time, as the pressure in the mold increases, the screw moves while injecting. When the material is filled in the mold, the injection machine injects the material into the mold by the action of back pressure. With the temperature of the material continues to decrease, the pressure in the mold cavity begins to decrease. When the injected material can be safely molded without being damaged, the injection mold is opened, and the product is ejected through the mold

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structure. Products that can be inlaid with the mold, and then the mold is closed for the next cycle.^[30-33] The external structure and size of the injection product are the exact structure and size of the internal mold of the injection machine, thereby replicating the mold-shaped product. Injection molded products often have many defects, such as short shots, sprays, sags, flow marks, weld marks, and floating fibers. These defects can be treated by subsequent processes such as spray coating, but it will increase the corresponding cost and time. The rapid heating-and-cooling cycle molding has become an effective solution to this problem.^[34] At the same time, controlling the parameters in the injection molding process is one of the effective means of manufacturing high-quality precision injection products. At present, injection molding technology has been applied in many fields such as optics, medical plastics, and drug delivery.^[35-37] Injection molding technology involves multi-disciplinary backgrounds.

Existing injection molding technology review articles mainly focus on the development and application of injection molding technology, such as the application of metal injection molding in medical equipment, and the applicability of metal injection molding technology to the manufacture of medical equipment. Some also report the limitations and needs for the preparation method, the microstructure and properties of the metal matrix composite materials. There is also an introduction to the theoretical knowledge in the injection molding process, a comprehensive introduction to the melting mechanism and shear mechanism during the injection molding process, and an analysis and introduction to a certain mixed system. In this way, there are many articles about the injection molding process and application, injection molding materials and injection molding mechanism.

The main contribution of this article is a comprehensive introduction to the entire injection molding process including injection molding equipment, injection molding molds, injection molding processes, injection molding materials and some special injection molding technologies. The injection molding of composite materials and micro-injection molding in recent years are also introduced with detailed examples.

2. Injection molding equipment, molds and processes

Plastic has gradually replaced many metal materials due to its light weight, stable chemical properties, good insulation properties, and low price, and has been widely used in high-end industries and daily life. At present, new materials represented by polymer materials are indispensable and have become one of the four major basic materials (steel, wood, cement). They are widely used in agriculture, machinery, medical, aerospace, automotive, and construction fields. The plastic industry is developing rapidly. The injection molding process can form a variety of complex shapes, sizes, and precise plastic products. It has

the advantages of short cycles, high efficiency, and high precision.

2.1 Introduction of injection molding machine

Injection molding machine, also known as plastic injection molding machine or injection machine, is used to add granular or powdery polymer raw materials to the injection molding machine barrel, melt and plasticize into polymers with good fluidity under the action of external heating and mechanical shear the melt, followed by the plunger or screw, quickly enters the mold cavity with a lower temperature, and is cooled and solidified to form a plastic product consistent with the shape of the mold.^[38] The injection machine usually consists of an injection system, a mold clamping mechanism, a hydraulic system, an electrical control system, a heating part and other auxiliary parts such as a cooling part and a feeding part. The following mainly introduces the injection system, mold clamping mechanism, hydraulic and electrical control systems.

As one of the most important components, the injection system is mainly composed of three parts: the plasticizing part, the injection part and the pressure driving part. Its functions are as follows: (1) Plasticizing- under the combined action of the screw and the heating ring, the material is melted and plasticized uniformly; (2) injection- one under the action of the screw, the plasticized material is injected into the mold cavity at a set pressure and speed; (3) the pressure is maintained- one molten material is injected into the cavity. Inside the cavity, the screw stays still to replenish a part of the molten material into the cavity to eliminate shrinkage caused by cooling, ensure product quality, and prevent material from flowing back.

The injection part is mainly composed of a pressurizing device and a driving device. When the melt in the metering section reaches the required amount, the screw stops rotating and remains stationary. Then, under the action of the injection cylinder, the molten material in the metering chamber is injected into the closed mold cavity under the setting of the injection process parameters, and the injection ends. The pressure device mainly provides power to make the screw exert pressure on the material. There are mainly two power sources: hydraulic pressure and mechanical force. At present, most of them use hydraulic pressure, and use self-sufficient hydraulic system to supply pressure.

The driving device mainly provides power to rotate the screw to complete the plasticization of the material. The most common drive devices are AC motors and hydraulic motors. Hydraulic motors are more commonly used. The advantages of using a hydraulic motor drive are: (1) softer transmission characteristics, smaller starting inertia, and protection of screw overload; (2) smooth screw speed adjustment; (3) small size, simple structure, and easy service.

As one of the main components of the injection molding machine, the mold clamping device is mainly composed of a mold closing device, a mold adjusting device

and an ejection device. The function of the clamping system is as follows: (1) to support the forming mold and ensure that it has an ideal speed change process when reciprocating between the open and closed positions, to avoid strong vibration during operation, to prevent the mold from being damaged by impact, and to achieve smooth ejection of products and increase productivity. (2) Provide sufficient clamping force to ensure that the mold can still be reliably locked under the action of the melt pressure to prevent the phenomenon of cracks in the slit and thus to ensure the quality of the product. To this end, the clamping parts and molds must also have sufficient strength and rigidity. (3) The product is cooled, the mold is opened, and a method for removing the product is provided. The clamping device is mainly composed of a fixed template, a draw rod, a power source, etc.

The working quality of the hydraulic system not only determines the technical performance of the injection molding machine, but also directly affects the quality of the product and the energy consumption of the injection molding machine. The composition of the hydraulic system is different, and is mainly determined by the operating cycle and performance requirements of the injection molding machine, which generally consists of power source (hydraulic pump), control elements (pressure valve, directional valve, flow valve, etc.), actuators (hydraulic cylinder, hydraulic motor, etc.) and auxiliary devices (oil tank, oil gauge, etc.). The actuator is controlled by the hydraulic circuit to complete the adjustment of each action program and parameters (pressure, flow) of the injection molding machine.

The injection molding machine has the following characteristics: the molded product has a complex shape,

high quality, and high precision; it can form metal insert products with good assembly and interchangeability; convenient and efficient product mold replacement, which is conducive to increasing product competitiveness; automation, simple operation and high efficiency. Modern injection molding machines are developing in the direction of high quality, high efficiency, and low consumption. Small and medium-sized injection molding machines are biased toward precision molding; while large-scale injection molding machines are biased toward low energy consumption, quietness, stable operation, and high efficiency.

In 2015, Engel developed the duo 500 pico series injection molding machine (Fig. 1). This series of injection molding machines uses a multi-variable pump system and some relatively advanced control technologies, so the injection molding time is very short. This shortens the empty cycle to 2.6 s, which has a greatly increased production efficiency, is currently the most advanced injection molding machine in the world. In addition, because the duo 500 pico series uses multi-variable pump technology, its energy loss is very small. In 2016, Battenfeld developed the HM400/ 3400 Advantage model (Fig. 1), with a clamping force of up to 400t. In the design process of HM400/3400 Advantage model, the high-efficiency and energy-saving double pump system is used. The maximum injection speed of this device has obvious advantages compared with other similar types of equipment, and can reach up to about 300 mm/s. In order to improve the working efficiency and meet a variety of work requirements, the Arburg S series injection molding machine is designed with dual pump and multi-pump control technology to meet the needs of simultaneous operations.

Fig. 1 Advanced injection machine.

2.2 Injection molding process

2.2.1 Precision injection molding

Injection molding technology can be divided into precision injection molding and conventional injection molding according to processing accuracy. Precision injection molding has incomparable advantages over conventional injection molding in terms of repeatability control, parameter control, and size control. For example, Michaeli *et al.*^[39] conducted in-depth research on factors affecting the precision injection molding process of aspherical plastic lenses, including mold design, process parameters and plastic raw materials. They used different injection process parameters and mold structures to perform actual injection experiments, and analyzed the degree of influence of process parameters and molds on the imaging quality of aspherical plastic lenses. The final experimental results show that compared to the mold design, the injection molding process parameters have a more significant impact on the imaging quality of aspherical plastic lenses. Zhang *et al.*^[40] used injection molding simulation software to optimize the design of molds for large injection molding products based on process monitoring and a series of experiments and verification, successfully predicting the deficiencies of microscopic features. The typical microfluidic chip was successfully copied using the injection molding technology to obtain suitable process data and simulation parameters. This method significantly improved the accuracy of the product. The process of using simulation software to predict and verify through experiments is shown in Fig. 2.

Young *et al.*^[41] used simulation software to study the effects of injection molding process parameters such as melt temperature, mold temperature, holding pressure, and holding time on the residual stress and warpage of plastic

lenses. The study found that compared with other injection molding process parameters, the effect of the holding pressure on the thickness direction of the plastic lens is more significant. Macías *et al.*^[42] repeated injection molding experiments and found that an improper selection of injection molding process parameters led to the generation of residual stress in the plastic lens, which significantly affected the structural size of the plastic lens. The stress method prolongs the service life of plastic lenses and increases the dimensional accuracy of plastic lenses, as shown in Fig. 3.

Holthusen and others^[43] used single-point diamond processing technology for ultra-precision processing of diffractive microstructures of injection mold cores. In order to study the degree of replication of different plastic materials on the surface of diffractive microstructures, they used three different plastics (i.e., poly(methyl methacrylate) (PMMA), cyclic olefin copolymer (COC), cyclo olefin polymer (COP)) for precision injection molding of mold cores with diffractive microstructures. The study found that PMMA as the same injection process parameters as the diffractive microstructured surface of the injection molding material is superior to the diffractive microstructured surface of the other two injection molding materials. Aidibe and others^[44] studied the influence of injection mold cores on the surface quality of light-emitting diode (LED) plastic lenses under different processing techniques. The study found that different types of surface textures cannot describe the surface quality with only a single parameter. Roughness is not the only parameter for evaluating surface quality of plastic lenses. At the same time, an important parameter was proposed to more accurately represent the quality of the plastic lens surface under different processing techniques, as shown in Fig. 4.

Fig. 2 Process monitoring and experiment prediction, with permission from [40] (Copyright © 2019 Elsevier Ltd.).

Fig. 3 Residual stress inside the plastic lens.^[42] (Copyright © 2015 Elsevier Inc)

Tasi *et al.*^[45–49] studied the influence of injection molding process parameters on the optical quality of small-diameter plastic lenses. First, the Taguchi method was used to screen the injection molding process parameters that affect the optical quality of plastic lenses. Second, the experimental data obtained from the full factor experiment was used to establish a multiple regression mathematical model. At the same time, a 5 mm plastic lens was used as an example to predict the quality of plastic lenses. The regression model was tested for surface accuracy, and the correctness of the injection molding process parameter combination was verified. A small-aperture plastic lens with a surface accuracy of 0.502 μm (PV) was injection molded, as shown in Fig. 5.

2.2.2 Multi-material injection molding

Injection compression molding is an advanced molding method to reduce the defects of traditional injection molded products. Injection compression molding is to inject polymer melt before the mold cavity is completely closed, and then apply uniform compression force or uniform pressure to the melt in the mold cavity. Therefore, injection compression molding is required. The injection pressure and clamping force are relatively small, which can effectively reduce the internal stress of the product, reduce molecular orientation, reduce birefringence, reduce uneven shrinkage

and warpage, etc., and improve the dimensional accuracy and stability, which effectively guarantees the performance of the product.

Injection compression molding will leave a certain gap when the cavity is closed, and makes the thickness of the cavity larger than the thickness of the product, and then fills in the cavity with the melt. At this time, because the cavity is wide at the beginning and its internal pressure is low, a lower injection pressures can be used. After the injection is completed, the injection molding machine clamping system performs the secondary clamping according to the control requirements. The clamping force is increased to push the movable template forward. Finally, the desired shape is formed, and then cooling is started. After cooling is completed, the product can be opened to remove the product.^[50] Injection compression molding can reduce the warping deformation and refractive index changes and improve the product dimensional accuracy, and is more suitable for molding precision optical devices. It is gradually becoming the preferred process for molding plastic optical parts. ABarnes *et al.*^[51] established and experimentally verified a non-linear viscoelastic theoretical model during the compression phase of injection compression molding. Kim and Isayev^[52] used the Leonov model to explore the differences between conventional injection molding and injection compression molding. It is found through research that the injection compression molding can effectively reduce the birefringence of the part compared with the conventional injection molding. Kwak *et al.*^[53] applied neural network technology to the field of computer simulation to improve the surface dimensional accuracy of optical components under injection molding processing, and conducted experiments to verify the correctness of the computer simulation results. Loaldi *et al.*^[54] used a method of checking Fresnel surface microstructure and process, a detailed evaluation of uncertain factors, effectively establishing the correlation between microstructures, improving the overall optical performance of the Fresnel lens. Bickerton and Abdullah^[55] studied the injection stage of injection compression molding, and found that the injection

Fig. 4 Lens surface texture measurement data for mold injection under different processing techniques, with permission from [44] (Copyright © 2017 Elsevier Ltd.)

Fig. 5 Small-bore imaging optical plastic lens, with permission from [45] (Copyright © 2008 Elsevier B.V)

compression molding can significantly shorten the injection time, and increase the clamping force and injection pressure.

2.2.3 Second injection molding

Two-shot injection molding is to inject two different (but chemically and rheological compatible) polymers into the mold cavity simultaneously or in a certain order.^[56,57] Products made from the combination of two different materials can provide special properties not available with traditional single resin injection molded products. Considering the recyclable materials and production costs, from the economic and ecological perspectives, secondary injection molding is one of the most promising processing methods. The secondary injection molding technology, also known as multi-component injection molding technology, was invented by researchers from the British Imperial Chemical Industry (ICI) in the early 1970s^[58,59] and used to produce foam core layers and solid shell layers of the shaped products.

There are many types of secondary injection molding,^[60] including sandwich injection molding (also known as core layer injection molding), overlap injection (overlay) molding, and two-color injection molding. According to different processes, the secondary injection molding technology can be divided into the following four types: single runner injection molding, dual runner injection molding, triple runner injection molding, and mono co-injection molding. According to the injection sequence of each component in its molding process, it can be divided into sequential co-injection molding and sandwich injection molding. It is the simplest and second earliest multi-component injection molding process used in industrial production.^[61] Sandwich injection molding is mainly to control different types of materials in a certain order. Through an injection molding nozzle, the shell of the product is molded from the first injection of the material, and the core layer is molded from the second injection of the material.

Sandwich injection molding is an important molding technology. Products with a shell layer and different types of core plastics can be formed by one injection molding. The reasons for this molding process to be generally accepted are: (1) It can be used to make shells and core layers with

different hardness, low shrinkage and good gas barrier; (2) The technology can be applied in new fields, such as waste recycling. According to the selection of the core material, such as low-density plastic with a structure similar to foam materials, the core injection molding can produce both large thick-walled parts and traditional thin-walled parts. In addition, the application of these low-density plastics can eliminate many defects caused by molding, such as shrinkage, deformation, cracking and internal stress.^[62]

The core injection molding of the injection process is listed as follows. First, material A is injected into the surface of the cavity to form a shell layer, and then material B is injected into A to form the core structure of the product. In order to obtain a stable product with a satisfactory cross-section, the shell and core materials should have similar rheological properties, such as similar melt index and molding conditions. Otherwise, when two plastics are injected, low- viscosity molten plastic tends to wrap around high-viscosity molten plastic. In addition, the thickness of the shell layer depends on the product wall thickness, melt viscosity, and molding conditions. The main purpose of applying this molding process is to obtain low-cost high-performance products by combining two plastics. To achieve this in a core mold, the chemical affinity and shrinkage behavior of these two materials must be similar.

Zang *et al.*^[63] studied the effect of core injection molding material viscosity and process parameters on the penetration depth and distribution uniformity of the core layer based on Moldflow. The results show that as the viscosity ratio of the core layer melt to the shell layer increases, the worse the uniformity of the core layer melt, the shorter the penetration length of the core layer melt is. Research also found that the core layer injection speed, melt temperature, and mold temperature have a greater effect on the penetration depth and distribution uniformity of the core layer. Overlap injection molding is to plasticize two different plastics in two injection molding machine barrels, and then sequentially inject them into the mold cavity.^[64] The first injection part is called the matrix material, and the latter injection part is usually semi-coated or coated. On the base material, plastic products of different colors or textures are formed, which is also called “in-mold assembly” or “in-mold welding” molding process.

Second injection molding has a very good price and quality advantage over traditional injection molding.^[65-67] In the production of thick-walled products, secondary injection molding is more suitable than traditional structural foam because the former has a better apparent quality. The combination properties that are difficult to obtain with a single resin can be achieved by combining different materials. In addition, the use of low-cost materials through the core structure can reduce product costs. Two-injection molding is one of the most effective production technologies for achieving high recycled material utilization, high repeatability,

and high-quality products.

2.3 Injection molding process parameters

High-molecular polymers undergo very complicated heating-cooling and mechanical shearing in the injection molding process. Due to different thermal-cold history and mechanical shearing history of polymer regions, the crystalline morphology in the thickness direction of the part is also different, and it will show a clear skin-core structure with an obvious anisotropy. The use of different injection molding process parameters will lead to different polymer microstructures. The differences in polymer microstructures are mainly manifested in the differences in molecular chain arrangement, molecular chain orientation, and crystallization. The differences in these microstructures of polymers will be different. Crystallization is also a major factor in the evolution of the aggregate structure and microstructure of the molded product, which has a significant effect on the physical properties and dimensional stability of the product. In the crystalline polymer, due to the incomplete crystallization of the melt, the polymer will contain two components: crystalline and amorphous regions.^[68] The physical quantity used to quantitatively describe the crystalline and amorphous regions is called the crystallinity of the polymer. Crystallinity is defined as the mass percentage (or volume percentage) of the crystalline phase in a polymer containing both crystalline and amorphous regions.

The impact of process conditions on the performance of the part is multi-faceted. Parts molded under different process conditions will have internal molecular structure differences at the micron level, and may cause a series of products such as bubbles, internal stress and shrinkage warpage at the macron level defect. A large number of studies have shown that the injection pressure and melt temperature have a greater impact on the mechanical properties of the part and reasonable control of the process conditions can effectively improve the mechanical properties of the product.^[69]

2.3.1 Melt and mold temperature

Increasing the temperature of the plastic melt will speed up the movement of the internal molecular chains and thereby achieve a better relaxation. The interaction energy between molecular chains will be reduced, the internal stress will be better released, and the internal stress will be smaller after the product is cooled. The degree of shrinkage and deformation is low, which makes the surface of the injection molded part smoother and shiny. For example, Wang *et al.*^[70] studied the residual stress of thin-walled parts and found that the mold temperature had a greater effect on the residual stress of the surface layer and the core region, and the pressure had a smaller effect on the residual stress. Wimberger *et al.*^[71-72] found that birefringence is related to the residual stress of the transparent material itself and the

product. Since the melt flow during the filling stage and the shrinkage abnormality is caused by the temperature and pressure difference during the injection molding process, the molecular orientation will cause the component generate internal stress. For example, Yao *et al.*^[73] used the injection molding simulation method to analyze the melt flow during injection molding, and analyzed the effects of various process parameters and mold sizes on the injection molding process. Under the condition that the mold temperature is low and the size ratio of the part is the same, for the part with a smaller thickness, it will normally require a greater maximum pressure and a longer injection time during injection. When the mold temperature is high and the size ratio of the part is the same, for the part with a smaller thickness, the maximum pressure required for injection does not change significantly, but a longer injection time is required. The maximum pressure required for injection molding also does not change significantly, and the maximum pressure is smaller when the injection time is short.

2.3.2 Injection pressure and speed

During the injection molding process, the melt undergoes a strong shear action in the barrel, and the injection pressure and injection rate are two process parameters that determine the shear strength of the melt. Injection pressure and injection rate are two related process parameters. Within a certain range, an increase in injection pressure will also increase the injection rate, which leads to an increase in the melt flow rate and an increased shear effect. Yang *et al.*^[74] used a measurement system based on Shack-Hartmann wave front metrology to evaluate the refractive index change of injection molded polymethyl methacrylate optical lenses at different filling pressures. It was found that under different holding pressures, the refractive index changes of the optical polymer injection molded lenses are larger, and the refractive index changes of the products under high holding pressure and lower holding pressure are more uniform. Yu *et al.*^[75] studied the effect of process parameters on the micro-filling properties of injection molded parts using a variable mold temperature injection molding. The results show that the injection speed and mold temperature have a greater impact on the surface replication performance of the part, indicating that the injection speed and mold temperature are the main factors affecting the surface gloss of the part. Chivatanasoontorn *et al.*^[76] studied the effect of injection speed (i.e. shear rate) on the microstructure of polypropylene (PP) surface layer. The results show that the ultra-high injection speed (1000 mm/s) can improve the crystal orientation and relative amount of β -phase crystals in the surface layer (0-30 μm). In addition, the effects of these microstructures on the surface properties were also studied through micro-cutting and progressive loading scratch tests. It was found that as the injection speed or shear rate increased, the surface strength and scratch resistance increased,

indicating the surface mechanical properties. There is a correlation with highly oriented microstructures on the surface.

2.3.3 Holding pressure and time

The main role of the holding pressure stage is to perform shrinkage after the molding is completed to avoid defects such as shrinkage due to volume effects caused by temperature reduction. Increasing the holding pressure will increase the shrinkage effect of the melt and increase the density of the part. In this process, part of the melt is still flowing, and this part of the melt will also be oriented due to the flow. In addition, due to the increase in density, the free volume must be reduced, and the mutual restraint effect of the molecular chains in the melt is stronger. The molecular chains need a longer time to relax, and the molecular chains that have already been oriented may reduce the de-orientation. The number ultimately leads to an increase in the degree of orientation of the article. If the holding time is prolonged, the melt density will increase, and the movement of the molecular segments will be more difficult. The size of the generated spherulites will be decreased, the haze will be decreased, and the transparency will increase. But as the melt cools and the gate cools and freezes, the effective dwell time will reach a maximum, and the dwell time will continue to be extended. The actual effective maximum dwell time will remain the same, and the haze will not change. Min *et al.*^[77] studied the influence of the filling and compression processes on the residual birefringence structure of the optical disc by testing the birefringence distribution and the extinction angle. Two anomalous birefringence and extinction peaks near the center in the thickness direction indicate the holding pressure, which indicates that the holding pressure has a certain effect when the flow is replenished during the holding phase. In addition, the injection/compression process has a more uniform birefringence distribution than products obtained by conventional injection molding. Weng *et al.*^[78-79] studied the residual stress and birefringence of microlens array precision injection molding through simulation and injection molding experiments. The residual stress and birefringence distributions obtained by simulation and experiment showed the consistency. The maximum residual stress always appears in the area near the gate, and the maximum value of the residual stress decreases with the increase of the holding pressure and the cooling time. The holding time has little effect on the maximum value of the residual stress. The most important process parameter that affects residual stress is the mold temperature, and the maximum residual stress value near the gate is smaller at higher mold temperatures. Lee *et al.*^[80] predicted the birefringence distribution of flow-induced and thermally induced residual stresses from the gate to the center by numerical simulation. It was found that the birefringence distribution of the stress birefringence values at the gate to the center was bimodal and generated

by heat, consistent with experimental values. Isayev *et al.*^[81] used a combination of finite element method (FEM) and finite difference method (FDM) for physical modeling and two-dimensional numerical simulation of injection molding. Residual flow birefringence in injection-molded parts is simulated by using a compressible nonlinear viscoelastic constitutive equation while considering the filling, packing, and cooling phases of injection molding. The simulation results show that in the absence of shrinkage, the birefringence of the surface layer of the part is mainly formed by flow stress cooling and solidification, and the core region is formed by thermal stress cooling and solidification. In the case of no shrinkage, as the shrinking melt continues to flow, a second birefringence peak will be formed between the product center and the position of the maximum birefringence, and the simulation results are consistent with the experimental test results. Pantani *et al.*^[82] studied the effect of different holding pressures on the molecular morphology distribution, and found that the holding pressure has a greater effect on the molecular orientation. Moreover, under a high holding pressure, a molecular structure different from that under normal pressure was observed. The molecular orientation under pressure decreases with the increase of the distance from the surface layer, and the structure of the skin-core structure is different. The molecular orientation of the high-pressure-preserving pressure component maintains a high value throughout the thickness, and even a second maximum value except the surface layer is observed.

2.3.4 Application of process parameters

As a result of the interaction of the injection molding parameters of the injection molded products, the mutual coordination between the parameters can not only keep the total product quality unchanged, but also achieve a reduction in energy consumption and improve product economics. For example, through the interaction of cooling time, screw speed, mold temperature and nozzle temperature, the total mass of the part can be maintained and the cycle time of the product can be effectively improved, which can effectively reduce the energy consumption in the production process and improve the economics of the injection molding process.^[83] During the injection molding process, the mold needs to be heated. Using this feature, injection molding can also optimize the temperature of the hot runner and the nozzle by controlling the coolant flow of the mold to achieve effective reduction of energy consumption and improvement of the injection molding process without compromising part quality.^[84] In summary, injection molding is a comprehensive process. In the actual production process, the injection molding parameters can be adjusted according to the characteristics of different materials to find the optimal parameters. This can not only keep the total injection quality unchanged, but also improve the economy benefit of the injection molding process.

2.4 Injection mold and injection process parameters

Many scholars have done a lot of research on injection mold and injection process parameters. For example, Yang *et al.*^[85] analyzed that in the process of mold forming, when the plastic parts have an arc structure, the use of ring gate for injection molding mold design will have a relatively large impact on the process parameters and precision of the plastic parts. The results show that the flow pressure holding stage has a great influence on the straightness and roundness of the plastic parts. Chang *et al.*^[86] studied the filling process of injection molding by injecting the resin reinforcement layer into the cavity area of the mold, because there were certain gaps between the moving mold and the fixed mold during the closing stage of material molding. The results showed that the filling time could be greatly reduced by speeding up the compression rate and narrowing the gap size. Lee *et al.*^[87] made a comprehensive analysis of the filling and flow pressure retention process, which not only made the pressure distribution of the mold cavity even, but also made the melt fill each mold cavity at the same time, so that the casting system reached the best and reached a balance in many aspects.

In order to improve the replication efficiency and reduce the cost, the micro-injection mold (WM) and micro-injection compression mold (ICM) are generally adopted to replicate the surface microstructure of thermoplastic polymer. Developed from traditional injection moulds, the core manufacturing component is the microstructure. Christiansen *et al.* produced a sawtooth microstructural surface with a certain angle, and successfully realized the anti-light reflection function of the microstructural region.^[88] Injection molding process parameters optimization of cell IM can significantly improve the replication quality of microstructures, thus effectively improving the adhesion and proliferation of cells in the polymer substrate.^[89] According to the characteristics of micro-injection molding, a rapid thermal cycling system has been successfully developed, which can quickly control the mold temperature to improve the replication quality of microstructures.^[90] Another assistive technique is the vacuum mold exhaust method,^[91] which aims to reduce the air resistance of the polymer into the microstructure. Sorgato *et al.* found through a systematic research that only when the mold temperature reaches a certain value, the vacuum technology can contribute to the improvement of microstructure replication quality, otherwise it will have the opposite effect.^[92]

3 Composite material injection molding

Composite materials have been widely used in industrial production, and they have gradually become one of the important indicators of a country's scientific, technological and economic strength. Advanced composite materials not only have excellent characteristics such as high strength and good heat resistance, but also have been widely used in

many fields such as aerospace, transportation and machinery. Composite injection molding is one of the current process methods for molding composite materials. The current injection molding method is the main method for molding composite materials. It is mainly prepared by injection of metal elements such as Ti, Mg, Al, and other metal materials and matrix resin composite materials.^[93] The injection molding process for most composite materials is mainly composed of the following four working steps. The first step is to dry the selected composite material at a certain temperature and dry it under a certain environment for a period of 2-3 hours. The second step is to put the dried composite material into a suitable injection molding machine and heat the injection machine to a suitable temperature to make the material appear molten. The plasticizing temperature is generally 230-250 °C and the plasticizing cycle is 15- 20 s. The third step of the work is to use the injection screw to inject the molten composite material into the mold, and cool the composite material in the mold to make the composite material with the mold cavity fixed to obtain the corresponding parts. It should be noted in this process that when the composite material is injected for 1-2 min, the injection should be performed after an interval of 1-2 min. After the injection, the mold should be cooled for 40-50 s. The fourth step is to remove the molded product. In the actual production process, an ion air gun can be used for rapid sweeping, and finally a product made of composite materials is obtained.^[94]

Composite material injection compression molding (IPM) technology was first developed by Japan's Mitsubishi Heavy Industries and Nagoya Machinery Works. Composite injection compression molding technology can be roughly divided into two parts: overall compression and partial compression. The overall compression injection molding technology refers to filling a resin into a model, and at this time, the model maintains a certain opening degree.^[95] Then the cylinder is compressed to move the mold until the mold is completely closed. Then the resin is refilled. The entire compression process is not relying on the entire moving film plate, but instead depends on the product molding surface on the stencil. The main advantage of this process is that it can make thin and light products with a lower pressure.^[96] Composite injection compression molding technology is generally suitable for relatively poor fluidity, but thin-walled products on the outside, such as polymer compounds PC and fiber-filled engineering supplies. In addition, the composite material direct injection molding technology proposed by the company is mainly applicable to materials with higher concentrations of glass fiber, C fiber, organic powders or inorganic powders.^[97] For example, injection molding of commonly used calcium carbonate composite materials and injection molding of wood flour composite materials can be performed by this method.^[98] In the preparation of composite materials, in order to highly disperse the fillers on the matrix resin, the traditional method requires the matrix

resin and the glass fiber to be fully mixed, and the assistance of a twin-screw extruder is required to perform out-of-process mixing. Pellets and then the corresponding products are obtained by the molding method. This method consumes a lot of energy, and also causes extensive degradation of the resin, oxidative discoloration, and excessive shearing of the corresponding fibers. Direct injection molding does not require pelletizing using an extruder. By blending it directly into the mixture, a product can be obtained. Because injection molding machines are mostly single-spiral devices, and their diameters are relatively small. Therefore, for injection molding technology, the most important thing is to improve the working efficiency of the screw rod.^[99-100] The injection molding technology of composite materials can be divided into resin-based composite material injection molding, metal-based composite material injection molding, and cement-based composite material injection molding according to different matrix materials used. They are introduced one by one in the following.

In the field of fiber composite materials, the ultimate goal is to produce low cost, high production efficiency and high-performance products through the composite of fibers and substrates. In the past decades, scholars have researched the resin-based glass fiber injection molding process. The main directions include: resin-based glass fiber composite fiber control and orientation research, resin-based glass fiber composite injection molding process parameter control and optimization and composite properties. Sun *et al.*^[101] mainly studied the injection molding process of long fibers. After obtaining production samples, by using a ray scanner, the fiber structure inside the sample was observed, and the fiber orientation was quantified to obtain the inside of the sample. The degree of fiber orientation in the outer layer, inner layer, and center layer of the tissue were determined. Eik *et al.*^[102] mainly studied the elastic properties of chopped fiber composites. Through simulation analysis, the fiber orientation distribution function of chopped fiber composites was established. Then, the comparison of experimental data was used to analyze the fiber distribution and the influence of elastic properties. Yahaya *et al.*^[103] mainly studied the forming process of pre-woven fiber composites. Their research mainly used experimental methods to compare pre-woven composite products with traditional processes. The universal electronic testing machine was used to test the various samples. Both the tensile strength and impact strength of pre-woven composite products were significantly better than traditional molding processes. Qi *et al.*^[104] mainly studied the fiber pavement forming process of fiber composite materials. Through theoretical analysis methods and simplified mathematical models, the failure forms of samples under compressive and tensile stress conditions were analyzed. Then, the fiber layer forming process was utilized to prepare the composite material samples under various layering angles. After comparing with the simulation data, the layering method of the fiber inside the product

directly affected the product performance, and the fiber of the layering structure was greatly improved. The mechanical strength of the sample and different lamination angles includes different effects on the performance of the product. Among them, the lamination molding at the 45° angle has the best performance, and its tensile strength is increased by approximately 112.5%. Bernasconi *et al.*^[105] mainly studied the anti-fatigue performance of chopped glass fiber composites with different structures. Under the same process, the fiber orientation in the test specimen was the same. V-shaped notches were opened on both sides of the test specimen, the fillet had a radius of 0.5 to 2 mm, and the fatigue resistance tests were performed on the test pieces with different fillet radii. The research showed that the smaller the fillet radius, the worse the fatigue resistance of the test pieces. Vincent *et al.*^[106] mainly studied the fiber orientation of chopped fiber composites with different fiber contents during the molding process. Composite fiber products have a better performance in the fiber orientation direction of the product. The fiber orientation behavior of the fiber composite material during the molding process was chopped fiber composite materials with a fiber content of 30% and 50%, respectively. The fiber orientation was monitored using the optical tracking technology, and the fiber flow behavior was analyzed.

The specific molding process of resin-based composite products mainly includes the following five. The first is the hand lay-up molding process, which uses manual or mechanical assistance to cover the resin-based composite material on the mold. This operation is extremely simple, but the process consumes time and is not suitable for mass production.^[107] The second is an injection molding process, which uses a spray gun to spray resin-based composite materials onto the corresponding mold and mold the product on the mold. This molding method is suitable for both short fibers and resin injection. The injection molding process has a relatively low cost and small losses, but uneven curing and pollution often occur.^[108] The third is the compression molding process. The finished product obtained by this process is more beautiful, efficient, and the size specifications are very close. However, its procedure is relatively complicated, and it is only suitable for the processing of small and medium-sized products. The fourth is the winding molding process, which not only has high production efficiency, but also has a relatively low cost. However, it is not possible to perform a winding treatment on a product with a concave surface. The fifth type is an autoclave forming process. The product produced by this process has a better treatment, but its disadvantage is that it costs more. In order to use resin-based composite materials more efficiently, the automation and specialization of the process should be actively promoted, so as to improve the development of injection molding technology.^[109] With the emergence of the energy crisis, light weighting is one of the main development directions of industrial products. The

body of the car, the floor and the brake parts, the aircraft frame and some avionics can be prepared by the resin-based composite material injection molding.

3.1 Metal matrix composite injection molding

Metal-based composite materials mainly use metals or metal alloys as the main matrix, and use metal or non-metal materials to make heterogeneous mixtures. Metal-based composite materials are divided into four categories according to the type of matrix: aluminum-based composites, nickel-based composites, magnesium-based composites, and titanium-based composites.^[110] The main performance characteristics of metal matrix composites are closely related to the properties of their reinforcements. Generally speaking, they have good electrical and thermal conductivity, and because of their small thermal expansion coefficient, they have good high temperature performance. In the processing operation, it is not easy to absorb moisture, not easy to age, and has good air tightness. Metal-based composites have become one of the topics for in-depth research by materials researchers due to their significant advantages. At the same time, there are certain problems at the interface of metal-based composite materials. Therefore, in the field of interface research, more attention should be paid to the development of favorable analysis methods. The existing interface reaction methods are optimized, more effective measures are proposed so as to truly promote the development of metal matrix composites.^[111]

Because of its many metal-based composite materials, its main matrix and reinforcements are also very different, so there will be a variety of molding processes. At present, the specific molding process of metal matrix composite materials mainly has the following three methods. The first molding method is a solid state method, the metal matrix and the reinforcement are in a solid state, and the entire process is performed in a low temperature environment. The second method is a liquid metal method. At this time, the metal matrix is in a molten state and a composite molded product is formed with a solid reinforcement. Because the preparation requires a higher temperature, the interface reaction must be strictly controlled, which is also the key factor for the success of this method.^[112] The third method is the self-generating method and other manufacturing methods, the main principle is that in the metal, an appropriate amount of a reaction element is added to generate a solid reinforcing phase through internal reaction. In addition, elements can also be deposited on the composite material layer by electroless plating or electroplating.^[113]

3.2 Cement-based composite materials injection molding

The cement-based composite material is a hydration reaction between cement and water, the hardened cement slurry is used as a matrix, and combined with organic materials, inorganic materials or metal materials to finally obtain a

cement-based composite material. Fiber-modified cement-based composites are most worthy of popularization in the application process, because the fiber-modified cement based composites can improve tensile properties and flexural strength.^[114] In addition, it can reduce shrinkage and cross-section size, which makes the component lighter. The fiber-modified cement-based composites are classified according to different fibers due to their different modes of action.^[115] Therefore, it is divided into four categories: short fibers, network fibers, profiled fibers and surface modified fibers. The toughness of fibers can be improved by improving the types of fibers and enhancing the properties and adhesion of the fibers. There are four more common types of fiber reinforced cement materials.

The first is a steel fiber cement-based composite material, which was first used in 1960. Its main performance characteristics are good impact resistance and sufficient toughness. In specific application practice, the effect of steel fiber on the cement-based composite materials is better than other types, and its performance occupies a certain advantage. It has been widely used in airport runway construction, bridge deck paving, ocean engineering construction, ballistic engineering and other projects. The second type is glass fiber reinforced cement-based composite material, which is very suitable for wrapping steel structures to improve the fire resistance. Since the material can suppress cracking, it can also prevent rusting. Therefore, it is extremely suitable for applications in the field of marine structures. Glass fiber is generally prepared by using quartz sand, dolomite, paraffin and other materials with strong acid and alkali. In some cases, oxides are added to assist in the preparation,^[116] for example, adding aluminum oxide, titanium dioxide and the like. In the specific application process, this kind of material is the most used fiber, and it is also an indispensable part of high-tech research and development. Because its raw materials are easy to obtain, its elasticity and stretchability are also relatively good. Therefore, it is also called one of the reinforcing materials with good performance. There are many ways to classify glass fiber reinforced cement-based composites. Among them, according to the alkali content in the raw materials, it can be divided into four categories: alkali, medium alkali, low alkali, and alkali-free glass fiber reinforced cement-based composites.

The third is polypropylene (PP) fiber reinforced cement-based composites. The appearance of the material enhances the permeability, and improves both wear resistance and impact resistance to the outside world. Specific applications are in aerated cement concrete and sprayed cement concrete. The fourth is smart cement-based composite materials, and refers to the composite smart components in traditional cement-based materials.^[117] For example, sensors or actuators are added to specific cement-based materials. Intelligent cement-based composite materials that have been used currently include navigation cement-based composite materials, self-

repairing cement-based composite materials, and temperature-monitoring cement-based composite materials. Among them, navigation cement-based composites are widely used in automobiles, and can be used to determine the specific driving route of automobiles with the assistance of electromagnetic waves,^[118] while self-repairing cement-based composites incorporate hollow capsules containing binders in composites. Once cracking occurs, it can be re-healed; temperature self-monitoring cement-based composite materials mainly rely on electrothermal effect and thermoelectric effect, and monitoring is implemented due to the changes in internal temperature. Specific applications include automatic snow and ice removal on airport runways and high-speed roads.^[119]

3.3 Carbon composite injection molding

Carbon composite is a combination of carbon fiber and resin, and its thermal expansion index is low. It also has high strength, fatigue resistance and other characteristics. There are four methods for processing carbon composite materials: hand lay-up method, injection molding method, winding method, and resin transfer molding method. Among them, the widely used, and the most suitable method for producing pipes is the winding method. Carbon composite materials can be injection molded by two methods, one is the impregnation method and the other is the CVD method. In general, there is still room for the progress in the composite materials science.^[120] Carbon composite materials not only have the inherent properties of carbon materials, but also have the soft characteristics of textile fibers. Because the carbon valence is relatively stable, it has excellent properties of resistance to strong acids and alkalis. Among the physical properties, it also has the characteristics of small friction coefficient, thus exerting the lubricity of carbon composites.^[121-122] In specific applications, carbon fiber composite materials can be used for bridge deck reinforcement, tunnels, and plant engineering maintenance. The basic principle of injection molding of carbon fiber composite materials is to accurately measure the two reactants, mix and collide under high pressure conditions, and then fill the mold. The mixture is fully mixed inside the mold, and a rapid polymerization reaction occurs to obtain the cured product.^[123] However, it should be noted that during this process, reaction monomers and reinforcing materials need to be mixed into the mold together to prevent the quick reaction. In specific research, researchers found that carbon fiber is a high-tech, and its products are unmatched by many other materials. At present, research on carbon fiber composite materials is mainly in the field of preparation technology and component analysis.^[124] With the continuous development of the market, the application of carbon fiber composite materials will be more and more. The development of carbon fiber composite materials has a profound impact on the molding technology and even the carbon fiber industry.

3.4 Other composite injection molding technologies

In the development of composites, attention needs pay to the changes of the matrix. The soft matrix is developed first, and then gradually transformed into a hard matrix. Evolving from resin to metal, a new type of ceramic matrix is now available. The ceramic matrix is generally called polyphase conformable ceramic, the trend of ceramic material researches from monolithic phase to multiphase will provide a wider space for the selection of the ceramic material design. Considerable improvement in mechanical properties of single-phase ceramic materials has been achieved by incorporating one or more other components into the base material to form ceramic matrix composites (CMCs). The reinforcing component is often in the form of particles or whiskers, such as TiC, TiN, TiB₂, SiC particulate, SiC whisker, B₄C, ZrO₂, WC, Ti(C,N), Cr₃C₂, NbC, etc. Ceramic composites are of increasing interest with the oxide matrices, particularly alumina being dominant. However, the corresponding material compositions, the processing techniques, the reinforcing and toughening mechanisms, the properties and their applications still need further study.^[125-129] Since it is a second-phase material introduced in the ceramic matrix, its toughness will be enhanced.^[130] Ceramic matrix composites have a low thermal conductivity, and have the advantages of high wear resistance, high temperature resistance, and corrosion resistance.^[131] In addition, it has become the most ideal high-temperature structural material today. According to relevant research, ceramic matrix composites will gradually become the material of choice for hot-end structures. Therefore, many countries have established related research in this field and hope to promote the development of composite materials.

Of course, there are many types of composite injection molding, such as self-reinforcing single polymer composites made by combining the same types of polymers with different characteristics into an object by co-injection.^[132] Traditional injection molding has a higher specific strength, no interface heterogeneity, and is easy to recycle. Foam injection molding (FIM) can be used to manufacture foamed PP/polytetrafluoroethylene (PTFE),^[133] fibril PLA/PET composites,^[134] PLA with polytetrafluoroethylene (PTFE) nanofibrils and polyhydroxyalkanoates (PHA). Other injection composite material components obtained through special injection molding processes are also examples of injection composite materials obtained by reinforcing each other.^[135] Of course, there are also other fillers added on the basis of the base material to obtain new composite materials through special injection molding methods, such as: manufacturing of isolated CNTs/high-density polyethylene (HDPE)/ultra-high molecular weight polyethylene (UHMWPE) is used to prepare conductive composite materials^[136] and PP-glass fiber/carbon fiber hybrid injection molded composite materials prepared by direct fiber feed injection molding (DFFIM) process.^[137] To sum up, the injection molding technology is a comprehensive process.

The products molded by the injection process can also be combined according to different needs of users.

4 The development and application of micron injection molding and related technologies

4.1 Micron injection molding

The concept of microinjection molding was first proposed since the 1980s. Micron injection molding refers to the process of pushing molten plastic from an injection machine into a micron mold and cooling in the mold to obtain a product under the action of a plunger or a screw. The schematic diagram of injection molding is shown in Fig. 6. After the material is plasticized in the heating barrel of the injection molding machine, the plunger or reciprocating screw is injected into the cavity of the closed mold to form the product. The injection molding method has the characteristics of processing complicated shapes, accurate dimensions or products with inserts, and high production efficiency.^[138]

1-template; 2-mold template; 3-plasticizing unit; 4-drive device;
5-plunger; 6-nozzle; 7-cavity

Fig. 6 Micron injection machine principle, with permission from [138] (Copyright © 2020 Elsevier B.V).

4.1.1 Classification of micron injection molding methods

Although the method of micron injection molding is not clearly defined, it is generally believed that the molding process applied to the production of the following three types of products or components can be referred to as micron injection molding: (1) the weight of the injection product is several micron grams to several gram, micro-injection-molded products with a size in the micrometer (μm) class, such as micron gears, micron pumps, micron motors, etc. There are many parameters that need to be controlled in the process of micron injection molding technology, such as temperature, pressure, time, pressure, injection speed and so on. Process parameters are very important in the process of injection molding. For example, Wang *et al.*^[139] produced micro-gears using semi-crystalline polyoxymethylene (POM) as raw materials by optimizing the mold, and obtained excellent properties of POM such as high mechanical properties and superior multidirectional stability, etc. The designed mold system is shown in Fig. 7.

(2) Molded products obtained by injection on traditional molds, but the molds themselves have microstructured areas or characteristic functional areas, such as arrayed lenses obtained by processing microstructures on different molds, microneedles obtained by microinjection. (3) Articles can have any size structure, but the size of the article is in the micrometer (or even smaller) order. For example, Piotter and others used micron injection molding technology to manufacture 16 different types of fiber optic connectors based on PMMA materials.^[140]

Fig. 7 Design of the mold system, with permission from [139] (Copyright © 2019 IOP Publishing Ltd.).

4.1.2 Micron injection molding equipment and process requirements

The products of micron injection molding technology have the characteristics of small size and high accuracy. In order to meet the special needs of microinjection molding in the production process, special equipment and molding dies must be used. Under normal circumstances, the following requirements should be considered. First, a small plasticizing device should be used. The diameter of the screw of an ordinary injection machine is in the range of 12 to 18 mm, and the screw length is short. The purpose is to avoid material degradation caused by long stay of the material. Secondly, accurate injection volume control and ideal injection speed control are critical. Due to the above special requirements, the injection machine itself is equipped with a separate metering and injection plunger and screw. The purpose is to accurately measure the injection volume and eliminate problems with material degradation due to shunts and dead ends of traditional injection screws. Moreover, in order to avoid the deformation of delicate micron injection molding, the precise positioning of the mold and the gentle mold switching speed are necessary. Finally, the special products are taken out of the shaped product for inspection and packaging. Because the size and weight of microinjection molded products are significantly different from traditional products, some specific steps must

Fig. 8 Injection mechanism of Microsystem 50. (a) Micron injection molding machine; and (b) Scheme of three steps in injection process, with permission from [146] (Copyright © 2008 Elsevier Ltd.).

be taken to ensure that the products are ejected correctly. For this reason, if a modern traditional molding machine is used for production, the original machine must be modified accordingly to meet the special needs of microinjection molding. However, with the reduction of product volume and injection volume, traditional injection machines are no longer an economically feasible solution. Many types of “microinjection machines” have been developed and put into commercial uses.^[141-143]

4.1.3 Applications of micron injection molding

With the rapid development of injection molding precision technology, microinjection molding products are used in optical communications, computer data storage, medical technology, biotechnology, sensors and actuators, micro-optical devices, electronics and consumer products, as well as equipment manufacturing and mechanical engineering. Applications in the field are on the rise. Typical examples of applications of injection molded products in life include: watch and camera components, car collision, acceleration and distance sensors, hard disk and optical drive read/write heads, micro-pumps, small spools, high-precision gears, pulleys and coils, optical fiber switches and connectors, micro-motors, etc.^[144-145]

Micro injection molding machine is featured with unique three independent mechanisms, consisted of plasticizing screw, a metering piston with an embedded pressure sensor, and an injection plunger. Since the injection unit is driven by cam mechanism, it exhibits excellent response for injection and stop motion. Therefore, this machine is suitable for manufacturing micro parts with high accuracy with stable molding.^[146]

4.1.4 The development of micron injection molding

In recent years, the main research directions of micro-injection molding technology involve the influence of process parameters on the micro-feature replication performance, improving the consistency between products, and finding the general law governing the influence of mold cavity roughness on the micro-feature replication. Progress has been made in obtaining the effects of mold temperature and injection melt temperature on the accuracy of micron injection molded products.^[147-148] Xie *et al.* found that mold temperature and injection speed are the main factors affecting micron injection welding marks. In the stage, ultrasonic vibration and physical vapor deposition (PVD) are used to process the corresponding films after molding, and even the strength of the thickness weld marks can be improved to greatly improve mechanical properties.^[149-150] Since the viscosity and rheological behavior of polymer melts are very different at macro and micro sizes, the study of their flow mechanism and rheological behavior under micro conditions should be strengthened. However, the minimum capillary diameter of capillary rheometers commonly used in experiments is 1 mm. Therefore, how to obtain rheological data of polymer melts at the micrometer scale has become the bottleneck of current research. Therefore, the corresponding experimental equipment is upgraded to complete the microscopic state. The following characterization is very important.^[151-152] At the same time, there are few studies on micro-morphology in micro-injection molding micro-structures. The current research lacks systematicity and diversity, and the main factors affecting the characteristic micro-structures of micro-structures are still unclear. Further research is needed to

develop new micro-injection materials, and further study the influence of different materials on the microstructure repeatability of micro-injection products. In order to promote the development of the injection industry, new micro-injection molding technologies such as gas-assisted micro-injection molding technology and multi-component micro-injection molding technology still have a lot of research work.^[153-154] Combining micro-injection molding technology with other micro-nano processing technology to prepare micro-injection systems with complex functions of multiple materials is also an important direction for future research in micro-injection molding technology.^[155-156]

4.2 Micron power injection molding

Micro-powder injection molding technology began in the late 1980s, and was first developed by the IFAM Institute in Germany based on traditional powder injection molding for the preparation of parts smaller than 1 μm in size. Micron powder injection molding is composed of metal powder injection molding and ceramic powder injection molding. It is a new metal and ceramic parts manufacturing technology. The micro-powder molding process is to uniformly mix solid powders with a certain polymer and additive components, and then granulate it in a certain method. In a heated state, a micro-injection molding machine is used to inject the granular material into the mold cavity to condense and then the chemical or thermal decomposition method is used to remove the binder of the formed product, and finally sintering and densifying is applied to obtain materials and products of various materials and shapes. The development of micro-powder injection molding technology has solved the problem of difficult-to-form complex products in the field of powder metallurgy for many years.^[157-161]

Recently, many polymer-based micro-components have been manufactured through micro-injection molding processes due to their material efficiency, productivity, and cost-effectiveness. The first challenge in microforming is to fill the microcavities as designed and expected.^[162] In conventional injection molding processes, flow is controlled by process parameters such as mold temperature, injection speed, holding pressure, and cooling time. These parameters are also critical for the microinjection molding process. However, the polymer melt flow in the microcavity may differ from conventional melts. As the scale of the system becomes smaller, the interface effects such as wall slip and surface tension become more apparent.^[163] Nevertheless, it is necessary to fully describe the characteristics of filling and filling flow. In addition to shear and inertial forces, the flow in the microcavity is also affected by the interaction of various forces (such as surface tension on the front and tensile viscous force at the entrance).

4.2.1 Characteristics and application of micron powder injection molding

Micro-powder injection molding can produce parts with

very small size or fine structure, or parts with a large overall size but with very small structures distributed in local areas, such as the mold silicon plate and clamp parts shown in Fig. 9. The structure size will generally be less than 1 mm.^[164]

Fig. 9 Die silicon plate and clamp made by micro powder molding technology, with permission from [164] (Copyright © 2013 Elsevier B.V.).

Compared with traditional injection-molded microplastic parts, micro-powder injection molding has significantly higher mechanical properties such as the strength, elongation, and hardness of parts. To reach high thermal conductivity as well as good electrical conductivity and high surface finish of products, the micro-powder injection molding places higher requirements on the particle size distribution of the powders, forming materials, forming processes, forming equipment and molds. Therefore, micro-powder molding can replace injection-molded microplastic products in many fields.^[165] However, many of the existing mature traditional injection molding technologies and theories cannot be fully applied to the field of micron injection molding. In order to promote the development of the micron injection industry, the technical characteristics of micron injection molding must be systematically and theoretically and practically combined for further exploration.^[166]

The micro-powder molding technology in the molding process is a small structure in the micron range, and the micro-structure is a molded structure copied from the mold surface. Therefore, the accuracy of the product during the powder molding process is not only determined by the surface quality of the mold insert. It also depends on the quality of the initial injection powders. Generally speaking, the micro-powder molding technology and the traditional injection molding technology have the same points. The products obtained by injection molding are a comprehensive product. The raw materials, processing machinery, and processing technology affect the final molding accuracy of the micro-powder products.

4.2.2 The development of micro injection molding

With the continuous development of micro-molding technology, the application field continues to expand. For the micro-injection molding technology, the method of manufacturing the micro-injection cavity also needs to be continuously improved. The problem of getter oxidation of pure powder and the problem of injection molding process

for flawless ultra-structured parts all pose great challenges to micron injection. Of course, the methods and various new processes for manufacturing micro-injection cavities are also developing rapidly. With the continuous emergence of new technologies, new equipment and new processing methods such as laser processing technology, the processing and maintenance costs of cavities will continue to decrease, and the micron injection molding technology will have broad application prospects in the field of MEMS manufacturing.^[167-168] At the same time, low-temperature micro-powder injection molding technology and low-pressure micro-powder injection molding technology will improve the accuracy and mechanical properties of the product.^[169-170]

5 Conclusions

In the field of manufacturing, polymer material presents advantages such as low cost, high machinability, good corrosion resistance, and biocompatibility. Thus, the development of polymer processing technologies such as injection molding has already become one of the research hotspots and vital developing aspects in the field of polymer industry. Injection molding is one of the most important parts of the polymer industry. This technology and related machines are also a world-wide big business, almost one third of the polymer products are fabricated by this method. Injection molding is a repetitive process, in which melted polymer materials are forced injected into the mold cavities. The heating of polymer materials in the plasticizing component, the forced injection of melted polymer materials into mold cavities, and the opening of the mold to eject the molded products are three basic operations during the injection molding process. Besides the injection molding for pure polymer materials, this technology is also developed for high efficiency processing of composite material as reviewed in this paper, including metal matrix composites, cement-based composite materials, carbon composites, and other composites. Moreover, new and improved methods are successfully being developed and applied in laboratories and industries. Although researchers around the world have already proposed a series of modified injection molding methods, significant improvements in processing efficiency and accuracy still need be made for the complete commercial viability of the process.

The future injection molding technology will continue to progress around the innovation of injection molding equipment, injection molding materials and injection molding technology. The injection molding equipment will combine with the development of science and technology to develop more intelligent and precise equipment. At the same time, the mold technology supporting injection molding technology will also develop in the direction of new material molds, high-precision molds, and replaceable molds. Injection molding materials will also have different types of development. The injection molding technology of

composite materials will gradually shape the research hotspot of injection molding technology. The injection molding process will also continue to be developed around the demand for high-precision, injection-molded products composed of different materials. In general, injection molding technology still has challenges in terms of equipment, materials, and processes that require researchers to continue in-depth research and continuously improve injection molding technology for different needs to gradually produce products that meet anthropological requirements.

Supporting Information

Not applicable

Conflict of interest

There are no conflicts to declare.

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