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NUMERICAL SIMULATION AND OPTIMAL CONTROL OF COMPOSITE NONLINEAR MECHANICAL PARTS CASTING PROCESS

HUAN LI* AND PENG WANG†

Abstract. In order to understand the numerical simulation and optimal control of the casting process of Machine element, the author proposed a study based on the numerical simulation and optimal control of the casting process of composite Machine element. Firstly, the author analyzed the structural characteristics of composite Machine element, introduced them in detail, and studied their casting technology in combination with the actual situation. Secondly, the casting process of composite Machine element was simulated by using numerical simulation method, and the temperature field and flow field in the casting filling and solidification process were analyzed. Finally, selecting square cylinders with different wall thicknesses as typical components, the scheme design of traditional single casting process and multi material composite casting process based on dieless casting composite forming technology were carried out. Finite element numerical simulation and experimental research were conducted on the two processes, respectively. The results indicate that: The casting obtained by the multi material composite casting process almost solidifies simultaneously around 200 seconds later, and the graphite morphology around the casting is Type A, with a length of about 100 um, with small differences and uniform distribution; The minimum difference in tensile strength around the casting is about 3.8%, and the maximum increase in tensile strength value is 21%. This research achievement can provide technical reference for high-performance and high-quality casting of complex iron castings. In order to improve the casting quality, the author optimized the casting process of composite Machine element by numerical simulation.

Key words: Composite materials, casting process, numerical simulation

1. Introduction. In the mechanical manufacturing industry, the application of composite material parts is becoming increasingly widespread [3, 10]. Due to the special properties of composite materials (such as dimensional stability, corrosion resistance, etc.) and their important role in mechanical manufacturing, composite parts are gradually replacing metal materials as an important component in the field of mechanical manufacturing. Composite material parts have many advantages compared to metal parts, such as light weight, high specific strength and modulus, good wear resistance, and strong designability. In addition, due to the differences in thermal physical and mechanical properties between composite materials and metal materials, the latent heat of phase change during the casting process is large, the heat transfer rate is slow, and the solidification time is long, these have had a significant impact on the casting process. Therefore, the casting process design of composite Machine element should fully consider the characteristics of large latent heat of phase change and slow heat transfer rate. Numerical Simulation and Optimization Control of Composite Machine element Casting Process During the casting process of composite Machine element, due to the different thermophysical and mechanical properties of composite and metal materials, the process of heat conduction and heat conduction during the solidification process is more complex. The use of numerical simulation technology can effectively predict and optimize casting processes, thereby shortening design cycles and reducing production costs. The mold filling and solidification process in the casting process has a great impact on the quality of the casting. For composite Machine element, the main component of the composite material is resin, and its latent heat of phase change is very large. If the composite parts are not pre treated (such as heat treatment, adding alloy elements, etc.) before pouring, it will lead to internal defects in the casting. In addition, due to the significantly lower thermal conductivity and thermal conductivity of composite material parts compared to metal parts, local overheating of the solidification site is prone to occur during the casting process. This Casting defect can be effectively prevented and controlled by reducing the filling time, shortening the solidification time and using materials with low thermal conductivity. The optimization design of casting process is to determine the optimal process plan based on the requirements of casting material performance, casting size,

*Xinxiang Vocational and Technical College, Xinxiang, Henan, 453006, China (Corresponding author: HuanLi32@163.com)
†Xinxiang Vocational and Technical College, Xinxiang, Henan, 453006, China (Email: PengWang2@126.com)

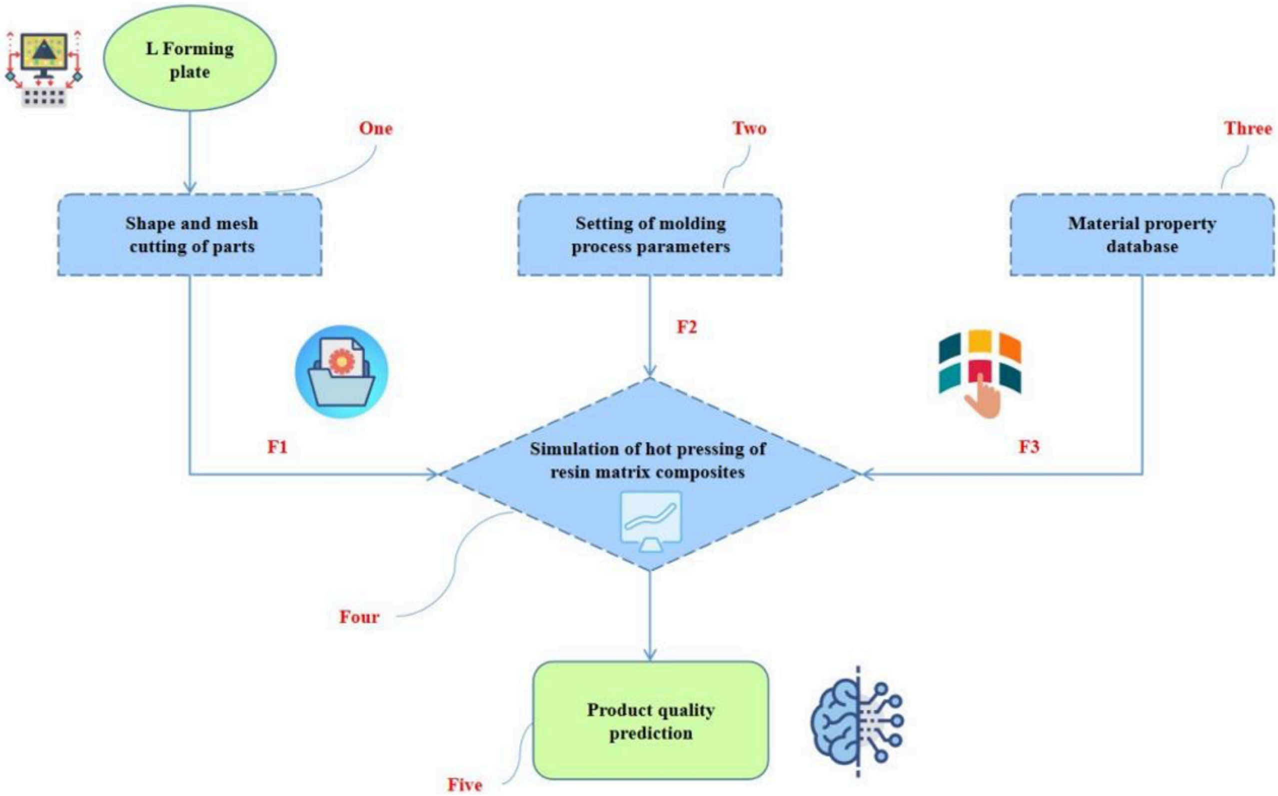


Fig. 1.1: Numerical simulation and optimization of composite machine element casting processlow

and casting structure; And the optimization design of casting process is an essential and important link in the casting production process, which is an important means to reduce production costs, improve product quality, improve labor productivity, and enhance the competitiveness of enterprises (Figure 1.1).

2. Literature Review. Machine element play a very important role in the production of modern enterprises, and composite Machine element are a typical composite structure, which have the advantages of light weight, high strength, corrosion resistance and good processing performance, and play a very important role in modern machining. Composite materials have the characteristic of anisotropy, and suitable casting processes need to be used during the processing to ensure product quality. At present, composite Machine element are mainly produced with resin matrix composites and Metal matrix composite. Resin based composite materials have the advantages of light weight, high strength, corrosion resistance, and good processing performance, making them a very ideal material. However, due to their anisotropic characteristics, traditional casting processes are difficult to ensure product quality in actual production processes. At present, the casting process numerical simulation of composite Machine element mainly uses computer numerical simulation technology to analyze the casting solidification process, and then optimize the casting process plan. By utilizing computer numerical simulation technology, it is of great significance to effectively predict and optimize casting process plans, thereby effectively improving product quality. Composite materials have the advantages of light weight, high strength, corrosion resistance, and good processing performance, which play a very important role in modern mechanical processing. However, composite materials have the characteristics of anisotropy, so suitable casting processes need to be adopted in production to ensure product quality. Composite Machine element are composed of metal materials and non-metallic materials, their interior is composed of multiple layers, and they also have certain anisotropy in structure, at the same time, because there are many pores in the interior, they are prone to appear shrinkage, porosity and porosity defects when casting them This is mainly due to the strong orientation of fibers in composites. When Machine element are in a certain temperature environment, fibers will undergo anisotropic deformation along the fiber direction. This is mainly because there are a large number of pores in the composite material, and during the casting process, due to the presence of many internal pores, it is easy to have defects such as uneven solidification shrinkage and difficulty in demolding the core during pouring. Composite Machine element also have anisotropy and isotropy, which have a great impact on the casting process. Therefore, in actual production, it is necessary to control and optimize it by adopting reasonable process measures. The application of numerical simulation technology in the casting process of composite Machine element plays a very important role in improving product quality and reducing production costs. Due to the complex structure, small thickness and high density of composite Machine element, therefore, multiple factors need to be considered during the design process, which increases the difficulty of the design. During the casting process, due to the high temperature of the molten metal and the anisotropic nature of the material, defects such as shrinkage cavities and porosity are prone to occur. And numerical simulation technology can predict the defects that occur during the casting process before casting, analyze the defects to determine the defect location and cause of the casting, and then take corresponding measures for optimization treatment. Numerical simulation of composite Machine element can effectively reduce the occurrence of casting defects and improve product quality.

Li, J. et al. evaluated the molten pool size under different process parameters by numerical simulation and SEM analysis, and the results showed a good agreement between the two. In addition, the effect of HA on the mechanical properties of sls was also studie [8]. Mulkapuri, S. et al., through different controlled experiments, can infer that bismuth-aquatic complexes are functional sites in response to OER. The overpotential of pH 13.0, pH 7.0 and pH 4.0 solutions was 375.0 mV(relative to reversible hydrogen electrode (RHE)), 585.21 mV(relative to reversible hydrogen electrode) and 830.10mV(relative to reversible hydrogen electrode), respectively. The catalytic conversion frequencies of bismuth-aquatic complexes were 1.24, 5.90 and 0.93-s-1, respectively [9].

3. Research Methods.

3.1. Mold design method of typical multi material composite machine element. Square cylinders with different wall thicknesses (8 mm, 10 mm, 15 mm and 18 mm) were selected as typical parts, which have uneven wall thicknesses and geometric thermal joints. Considering that the cast iron parts should approximately satisfy the principle of simultaneous solidification and the mechanical properties are expected to be uniform, the square barrel is split into six sand units. The sand setting of each sand unit was calculated, and four sand units with different wall thickness edges were obtained, and different types of sand were applied, and resin silica sand was used for the sand core unit and the base sand unit. As shown in equation (3.1)

$$t_f = (0.94 \sim 0.97)\frac{\pi \rho_s L^2 V^2}{4\lambda_m c_m \rho_m A^2 \left(T_m - T_0\right)^2} = (0.94 \sim 0.97) \tag{3.1}$$

In the formula: T_m is the melting point of the metal casting, T_0 is room temperature, °C; P_s is the density of the metal casting, kg/m^3; L is the latent heat of solidification, W/m^3; B_m is the heat storage coefficient of the mold.

3.2. Finite element numerical simulation of typical casting process.

3.2.1. Establishment of finite element model for typical components and pre processing loading. Using the casting/mold integration modeling method, first build the Geometric modeling of the cubic cylinder and its mold [6, 16]. And then divide the surface grid and volume grid of the mold and casting assembly through the MeshCAST function module in ProCAST software. This grid division mainly adopts tetrahedral grids, and local grid refinement has been applied to important parts.

The pre processing module Precast of ProCAST software sets the thermal properties parameters, gravity parameters, boundary conditions, interface heat transfer coefficients, and casting materials for the finite element models of each specimen, as shown in Table 3.1.

3.3. Numerical simulation of temperature field during solidification process of typical components. In this study, the temperature field of the traditional Machine element casting process and the composite Machine element casting process of the square cylinder were numerically simulated, respectively, to

Table 3.1: Pre processing conditions settings

Parameter Name	Design parameter settings
Casting material	Casting: Gray iron 260
Interface heat transfer coefficient	Reference self test results
boundary condition	Pouring temperature: 1460 ℃
Gravity parameters	Direction: Gravity direction (vertically downwards)

obtain the solidification time (that is, all the liquidus time) [15, 12]. According to the numerical simulation results, there is a significant difference in the solidification time of the four sides of the square cylinder in traditional casting processes. The solidification time of the thinner edges reaching the liquidus is about 300 seconds, while the solidification time of the thicker edges is about 650 seconds, with a difference of about 50% [5, 14, 11]. The composite casting process uses chromite ore sand with stronger heat storage capacity for the thicker side, and uses the quartz sand with stronger heat storage capacity for the thickest side, so the solidification time of all sides of the casting is about 300 s, almost achieving simultaneous solidification [18, 4].

3.4. Numerical simulation of metallographic structure and mechanical properties of typical parts. This study conducted numerical simulations on the metallographic structure and mechanical properties of cast iron castings obtained from traditional and composite material casting processes of typical castings [20]. The thinnest edge of graphite volume fraction is about 0.01, the thickest edge is about 0.0137, and the tensile strength value is about 420 MPa for the thinnest edge and 360 MPa for the thickest edge. The graphite volume fraction around the square cylinder obtained by the composite material casting process is about 0.133, about 420 MPa. From the numerical simulation results, it can be seen that there is a significant difference in graphite volume fraction and tensile strength values around typical castings in traditional casting processes, and the tensile strength value is almost the same, indicating that the overall mechanical properties of the typical component are uniform and good.

4. Experimental Analysis.

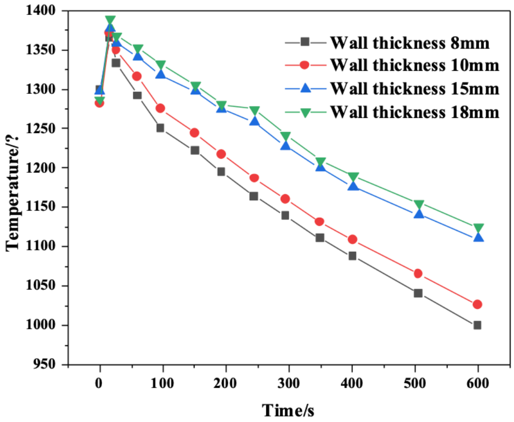
4.1. Typical casting process test steps and conditions. The ratio of various types of sand is: alkaline phenolic resin accounts for 3% of the weight of the original sand, and curing agent accounts for 30% of the weight of the resin. Cut and process each sand mold unit on a digital dieless casting precision forming machine, and assemble each sand mold unit into a mold to be poured [1]. When the temperature of the molten iron reaches 1460 ℃, pouring is carried out to obtain a square cylinder casting.

4.2. Temperature field test for solidification of square cylinders. The real-time temperature value during the solidification process of the square cylinder measured by a high-temperature thermocouple embedded in the mold is shown in Figure 4.1(a) (b).

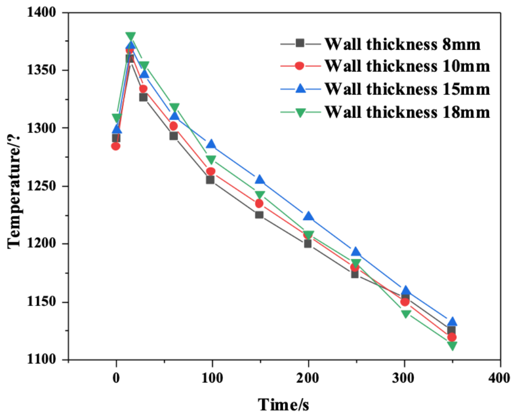
According to the results, the temperature field test results of the solidification process of square simple parts are consistent with the finite element numerical simulation results: In traditional casting techniques, the solidification time of square cylindrical parts varies greatly from the beginning of solidification to the liquidus. The solidification temperature gradient of the thinner edge is larger, while the solidification temperature gradient of the thicker edge is smaller. At 100 seconds, the solidification temperature difference at different wall thicknesses is 80 ℃. In the composite casting process, there is a slight difference in temperature gradient at the beginning of solidification on the four sides of the square cylinder. At 100 seconds, the solidification temperature difference at different wall thicknesses is 45 ℃, and after 210 seconds, the temperature gradient is almost the same, achieving simultaneous solidification.

4.3. Metallographic structure testing of square cylinder parts. Cut and grind typical pieces obtained from traditional casting processes and composite material casting processes, and observe the graphite distribution morphology and length under a high-power optical microscope.

During the solidification process of castings, the cooling rate depends on the thickness of the casting wall, and there is a significant difference in the cooling rate between the thick walled and thin-walled parts of the



(a) Traditional casting process



(b) Composite molding process

Fig. 4.1: Measured temperature during the solidification process of a square cylinder

Table 4.1: Tensile strength of square cylinders

Wall thickness /mm	Tensile strength of typical components in traditional casting processes/MPa				Tensile strength of typical components in load material casting process /MPa			
	1	2	3	average	1	2	3	average
9	303	310	321	311.33	310	304	315	309.66
12	285	294	300	293	306	308	302	305.33
16	242	260	250	250.66	297	300	294	330.33
20	240	245	244	243	289	285	290	288

casting. The graphite morphology of parts with significant differences in wall thickness of the same casting may also vary. For example, traditional casting processes have significant differences in graphite morphology and length around castings with different wall thicknesses. The graphite morphology includes A type and A+E type, with a length of 100-300 um. The composite material casting process uses different types of molding sand with different heat storage capabilities for different wall thicknesses, resulting in a graphite shape around the casting that is similar to Type A, with a length of about 100 um, with small differences and uniform distribution.

4.4. Mechanical property testing of square cylinders. The tensile strength of typical specimens cut from traditional casting and composite material casting processes is tested on a universal material testing machine, as shown in Table 4.1 and Figure 4.2.

According to the test results, the tensile strength values of the four sides of the square cylinder obtained by the traditional casting method are different, the maximum value is 311.33 MPa, and the minimum value is 240 MPa. A difference of about 20. Approximately less, the maximum value is 330.33 MPa, and the minimum is 285 MPa, with a difference of about 4. This indicates that the overall mechanical properties of the typical component are approximately uniform and consistent, and the maximum increase in tensile strength value of the casting is 21%. The reason for this is that the graphite size around the square cylinder obtained from the composite material casting process is small, similar in length, and evenly distributed, resulting in an increase in the tensile strength of the thick wall and a small difference in the overall strength of the casting. In addition, there are some differences between the tensile strength test results of typical components and the strength values of finite element numerical simulation results, but it has no substantial impact on the test results [17, 19, 2, 13, 7]. This is because the performance parameters of the HT250 material used for pouring after inoculation treatment

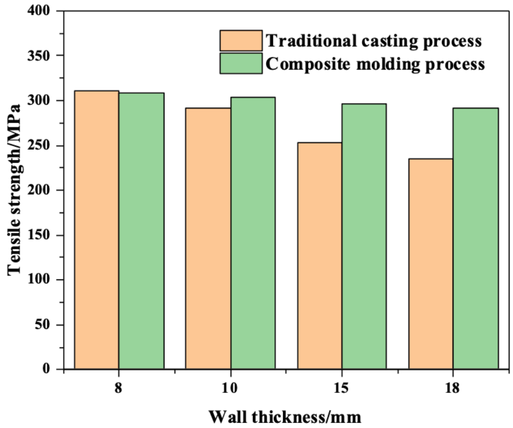


Fig. 4.2: Comparison of tensile strength of square cylindrical components with different wall thicknesses

differ from the performance parameter values of HT250 in the ProCAST software material library.

5. Conclusion. (1) In traditional casting processes, the solidification time of all four sides of a square cylinder reaching the liquidus varies greatly. The thinner edge solidifies first, while the thicker edge solidifies last. At 100 seconds, the temperature difference between different wall thickness edges is about 96 ℃. In the composite material casting process, there is a slight difference in temperature at the beginning of solidification on the four edges of the square cylinder. At 100 seconds, the temperature difference between different wall thickness edges is about 35 ℃, and after 200 seconds, almost simultaneous solidification is achieved.

(2) The graphite morphology and length around square tube castings with different wall thicknesses obtained by traditional casting techniques vary greatly. The graphite morphology includes A type and A+E type, with a length of 100-300 um. The graphite morphology around the castings obtained by the composite casting process is all A-type, with a length of about 100 um, with small differences and uniform distribution.

(3) The tensile strength values of the four sides of the square cylinder cast by traditional Machine element differ greatly by about 24%. The difference in tensile strength values around the square cylinder obtained from the composite material casting process is small, with a difference of about 3.8%. The overall mechanical properties of this typical component are approximately uniform, and the maximum increase in tensile strength value of the casting is 21%.

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