The Through Process Simulation of Mold filling, Solidification, and Heat Treatment of the Al Alloy Bending Beam
Low-pressure Casting

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Abstract: The research on the simulation for the through process of low-pressure casting and heat treatment is conducive to combine information technology and advanced casting technology, which will help to predict the defects and mechanical properties of the castings in the through process. In this paper, we focus on the simulation for through process of low-pressure casting and heat treatment of ZL114A Bending beam. Firstly, we analyze the distribution of the shrinkage and porosities in filling and solidification process, and simulate the distribution of stress and strain in the late solidification of casting. Then, the numerical simulation of heat treatment process for ZL114A Bending beam is realized according to the heat treatment parameters and the corresponding simulation results of temperature field, stress, strain, and aging performance are given. Finally, we verify that simulation platform for the through process of low-pressure casting and heat treatment can serve the production practice perfectly and provide technical guidance and process optimization for the through process of low-pressure casting and heat treatment.

1. Introduction
The through process or whole process of casting generally consists of many continuous complicated process such as mold design, alloy pouring and heating treatment and so on. Each of them has mutual effect and may seriously affect the casting quality. For example, the design defects in mold design have an important impact on the pouring process and usually result in a lot of reject castings. In turn, successful mold filling require the rationality and feasibility of mold design. And much of alloy pouring process may produce the defects of shrinkage porosity and shrinkage cavity in castings. Then, heating treatment will be adopted to eliminate the casting defects.

In order to obtain these high-quality castings, it is essential for complex structures of castings to conduct process design analyses. And there are lots of methods [1-3] in which the numerical calculation applied for this process can quickly and accurately simulate the forming process and predict tissue defects of castings, thereby the optimization result of process design can be achieved. More researches were focused on a particular process above such as YUWEN et al [4] and Choudhari

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et al [5] and Zhang [6]. Moreover, casting filling process is tightly coupled with solidification process. Therefore, the influences of coupled process in whole process of casting were also undertaken, including Paul et al [7], Anglada et al [8], Miller et al [9] and so on. However, at the present stage, the requirements of the Foundry Engineering Technology is to better serve the actual production, since the forming process of a cast that includes more continuous physical and chemical changes, and the ultimate mechanical properties or casting quality is affected by the combined effects of these processes rather than just a single liquid metal filling process or solidification process or heat treatment process, etc. Accordingly, this paper is based on professional and advanced whole process simulation platform for casting forming and heat treatment. The whole process of aluminum casting ZL114A of bending beam by low pressure, covering filling, solidification and heat treatment process, have been numerically calculated. And a comprehensive analysis and forecast results for the tissue forming defects and mechanical properties in the process have been achieved and expected to provide the subsequent analysis of the whole process reference.

2. Process scheme of aluminium alloy casting by low-pressure

2.1. Geometric model

Figure 1(a) shows a sketch of the prototype. The overall size of this casting is 826mm × 169mm × 330mm. According to the technological and structural characteristics of aluminum alloy castings by low-pressure, its requirements must be to fill molten metal smoothly and to ensure that aluminum alloy molten metal is not easily oxidized. Therefore the pouring gating system is set as the expansion system, the flow gate is conformal, the size of cross gate is 60mm × 50mm and the diameter of rising pipe is 70mm. Then a three-dimensional model with pouring gate system is established by three-dimensional software as shown in Figure 1(b).

(a) Sketch of the prototype         (b) Assembly model with pouring gate system

*Figure 1.* Prototype and assembly model of aluminum alloy bending beam.

2.2. Flow process diagram of simulation

In this paper, the main casting process, including filling process, solidification process and heat treatment, have been analyzed in the following. First, by requirements of casting, the casting materials and geometric model are carefully designed. Then the data of geometric model is applied into the filling process simulation in which the information of temperature and fluid flow field are obtained. On one hand, the information can be fed back to the data of mold design. On the other hand, it also flows into the next process, i.e. solidification process. Subsequently, based on the previous results, the solidification process is simulated. Likewise, the temperature and stress-strain field are also obtained, and it affects the mold design and guides the heat treatment. Finally, a high-quality casting process is designed. And the flow process diagram of simulation is shown in Figure 2.
3. Mathematical models and boundary conditions

3.1. Mathematical models
Since this paper is based on the numerical simulation of the whole process platform, the whole process from cast form to heat treatment has been numerically simulated, including the flow field, the temperature field and the stress field. The mathematical models mainly consist of equation of continuity, momentum equation, equation of heat conduction and stress-strain equation [9-10].

3.2. Boundary conditions
The casting material of aluminum alloy is ZL114A, the physical parameters of which are as follows (1), (2) and (3) and shown in Table 1.

\[
\rho (\text{kg/m}^3) = 2681.35699 - 0.20259 \times T \\
\lambda (\text{W/(m K)}) = 152.0237 + 0.04223 \times T \\
C_p (\text{J/(kg K)}) = 885.66921 + 0.44541 \times T
\]

Table 1. Physical parameters of calculation.

| Parameters                          | value  | Parameters                          | value  |
|-------------------------------------|--------|-------------------------------------|--------|
| Coefficient viscosity/(m²/s)        | 2×10^{-6} | Heat transfer coefficient(W / m² K) | 962.7  |
| Latent heat/(kJ/kg)                 | 418.6  | Threshold of solid fraction         | 0.625  |
| Liquidus temperature(°C)            | 615    | Liquid shrinkage rate               | 0.00005|
| Solidus temperature(°C)             | 555    | Shrinkage rate of phase transition  | 0.03   |
| Pouring temperature(°C)             | 720    | Young's modulus (GPa)               | 67.8   |
| Pouring time(s)                     | 3      | Poisson's ratio                     | 3.72   |
The heat treatment conditions of casting are as follows:

(i) The cast aluminum is heated to 540 °C and kept warm in 10 hours, then cooled down at the temperature of 80 °C in water.
(ii) Aging treatment in 165 °C and heat preservation of 8 h in air.
(iii) It is a free state at entire process of heat treatment and cooling treatment.
(iv) According to the simulation, the creepage is considered during heating.
(v) The elastic-plastic model is applied in the simulation process.
(vi) The relationship between strength and cooling rate in quenching are as follow (4) and (5) (R represents the average cooling rate between 450 ~ 200 °C).

\[
\sigma_m(MPa) = 29.55 \times \log(R) + 289.5
\]

(4)

\[
\sigma_s(MPa) = 30.45 \times \log(R) + 233.12
\]

(5)

4. Simulation results and analysis

4.1. Mold filling process

Filling process is one of the key to casting quality, which involves a liquid metal flow and temperature fields coupled. And its various parameters such as filling velocity and temperature directly affect the cast form. So it is necessary to first study the filling process. Meanwhile, the effects of casting pouring system and bending beam structure on filling velocity and temperature should also be researched. Each stage of Correlated Color Temperature for filling process is shown in figure 3(a), (b), (c).

![Correlated Color Temperature](image)

(a) t=0.51s  (b) t=1.12s  (c) t=2.65s

Figure 3. Correlated Color Temperature of filling process.

Figure 3 shows that, in the beginning of filling process, high-temperature liquid metal at low pressure is slowly rising from the riser tubes and smoothly split within the cross gate, which reduces the gas entrapment and inclusion for high temperature liquid metal in a certain way. Especially for aluminum alloy casting, this method has the advantage of preventing oxidized. Subsequently, the temperature drop of liquid metal in frontier is excessive with respect to other zones. But the low-temperature liquid metal is heated by follow-up high-temperature liquid metal, thus promoting that the molten metal fill forward in small temperature range until the entire cast is fully filled. Meanwhile, in the junctional area between cross gate and flow gate, the temperature drop is obvious as well as in both ends of the bending beam castings. For this situation, there are numerous and diversified reasons, which include the sudden change in the flow direction of the molten metal, the occurrence of turbulent flow and the more heat loss. And these reasons also bring about that the high temperature liquid metal flow forward in transient delay and cannot provide a continuous flow of heat.
for the leading edge of the molten metal, resulting in a big temperature drop of molten metal at the leading edge. In addition, at the final filling region of the bending beam casting, the temperature is significantly less than the other regions.

4.2. Solidification process

4.2.1. Cooling rate of solidification.

When the filling process is finished, the molten metal becomes solidified simultaneously. And the solidification process is influenced by a number of factors [11-12], such as filling process analyzed above and temperature variation. From the macro perspective, the solidification sequence is determined by the filling process and temperature variation, which contribute to composition segregation, shrinkage, cracks in solidification process; from the micro perspective, the microstructure forming in the solidification process is determined by the nucleation process.

At last, the mechanical properties of the casting are affected by these factors, wherein the cooling rate of solidification process is a key problem. To study the law, the cooling curves are plotted and analyzed in terms of four different points selected from the casting, as shown in Figure 4(a), (b).

![Figure 4. Cooling curve of solidification process.](image)

In figure 4, all the four cooling curves of aluminum alloy castings show distinct variation law. As soon as the filling process come to an end, the casting temperature decline rapidly. When the temperature go down to about 620 degrees that is close to the liquidus temperature of the casting, all the cooling curves appear to horizontal but different degrees. In the first place, it is the coordinates of A at the cross gate in which the trend of the cooling curve is more smooth and linear with time. In the next place, the coordinates of B is located at the junctional section between the cross gate and flow gate, its cooling curve is relatively flat and easy. But when the temperature decreased to about 560 degrees that is close to solidus temperature, the inflection point appear. Then the trend of cooling curve tends to be declined; finally, the coordinates of C and D are separately located at the top end and central region of the bending beam, in which the trends of two cooling curves coincide with each other and also show a gradual lesser extent. Likewise, when the temperature is then decreased to about 560 degrees, there is a sharp decline until approximately 250 degrees. It is analyzed that, the above variation in the same kind of aluminum alloy castings is mainly determined by the process scheme of aluminum alloy castings in low-pressure casting. On the one hand, in the low-pressure casting, the casting mold is filled with molten metal from the down to top, forming the solidification process in proper sequence of central section, top end, junctional section and cross gate that is from top to down. On the other hand, owing to the sequence of solidification process, the casting produce the macrosegregation, and the later solidification location of the mold cannot be fed with molten metal, thus resulting in a different cooling curve.
4.2.2. Stress and strain distribution of solidification process

In the late stage of solidification, different cooling rate in the portions of the casting result in uneven distribution of the temperature. And the cooling metal is to shrink and be blocked that produce shrinkage stress. This stress can cause the cracks of the casting and a more serious impact on the serve life. Therefore, to provide guidance for the subsequent heat treatment of castings, it is necessary to analyze the stress and strain distribution of solidification process. Because of the correspondence between stress and strain, the stress distribution is analyzed only. It is shown in figure 5(a), (b) for different times of stress distribution.

![Stress distributions in the various stages of the solidification](image)

(a) t=124.01s  (b) t=442.66s

**Figure 5.** Stress distributions in the various stages of the solidification.

In figure 5, the stress distribution is ever-changing with time and similar to the distribution of shrinkage porosity and shrinkage cavity above. In the early stages, the stresses gradually appear in the boundary of the bending beam. Subsequently, there also appear stresses from outside to inside and to extend to the bending beam casting ends. Meanwhile, the stress is gradually increasing and the maximum stress emerges in the place where the stresses appear in the beginning stages. It is because that the stresses and shrinkage properties are all affected by the temperature changing with time in the solidification process. So it is assumed that the shrinkage properties or mechanical properties are influenced by the stress in the late stage of solidification. And a follow-up heat treatment is necessary to relieve the casting stress and improve the mechanical properties.

4.3. Heat treatment process

In the actual production there are more or less casting defects in filling process and solidification process, although the optimization results which was obtained by analysis of the previous coupled process are helpful for controlling defects. To further eliminate the casting defects, appropriate heat treatment is indispensable [13].

In general, a cast after filling process and solidification process is directly heated by accumulation of experience or little instruction from previous processes, thus resulting in a higher defective index. Namely, the whole process parameters cannot be seperated from each other for a high quality casting. Besides, the continuation of the flow of process parameters in whole casting process also can promote the increase of efficiency. Here, a professional simulation platform of whole process is developed to continuously simulate the heat treatment. In that way, the temperature and stress-strain field of the bending beam above is applied into the simulation of heat process. Heat treatment in this article consists of heating process, cooling process and aging treatment.
4.3.1. Heating process

In the heating process, the temperature field of casting is changing with time and its surface temperature is not uniformity, which produce the stress and deformation. So the temperature field and corresponding stress or deformations need to be researched in this part, as shown in fig. 6 (a), (b).

![Temperature field and X-displacement](image)

**Figure 6.** Temperature field and its corresponding deformations in heating process.

In fig. 6, when the casting is heated to a temperature between about 137 degrees and 141 degrees, the corresponding X-displacement varies from -0.243mm to 0.228mm and the results also show that there exist obvious symmetry variations for the displacement. That is because the difference in temperature is not big, though the temperature field is not uniformity. At this moment, the heat-up time is about 3870s, just in its beginning stage. In general, the maximum and minimum X-displacements decrease to certain values that can be ignored at last. It shows that the casting deformations caused by stress are relieved. From the above, it is concluded that the temperature field distribution is similar to the X-displacement on the whole, that is to say, the absolute values of temperature and X-displacement are big in the end and small in the middle. There are two reasons for this distribution law. First, at the beginning the high temperature is located at the edge of casting, and then the heat energy is transferred from edge to inside. But the total energy is on the increase. Second, as the temperature rises, the casting deformations are transferred in the opposite direction. And the maximum deformations at the edge of casting are accumulated through this transfer process, thus forming the distribution law.

4.3.2 Cooling process

Similar to the heating process, temperature reduction also cause the casting stress and deformations. But there are different reasons for this temperature field and X-displacement distribution in cooling process, as shown in figure 7(a), (b).
Figure 7. Temperature field and its corresponding deformations in cooling process.

In fig.7, different from the temperature field in the heating process, the high temperature in cooling process is located at the inside of casting. And the corresponding maximum X-displacement is still located at the edge of casting. As the temperature decreases, the heat energy is transferred from inside to edge and the casting deformations or X-displacement caused by casting stress is on the increase and transferred in the same opposition. And the maximum deformations at the edge of casting are also accumulated through this transfer process. As shown by the numerical results, when the casting is cooled down to a temperature between about 80 degrees and 80.9 degrees, the corresponding X-displacement varies from -1.07mm to 1.18mm. The absolute values of temperature are big in the middle and small in the end. On the contrary, the absolute values of X-displacement are big in the end and small in the middle.

4.3.3. Aging treatment

Generally speaking, the hardness and strength of cast by quenching process are not immediately to be maximized, especially for the aluminium alloy. To obtain the high-quality casting, the aging treatment is to be needed after heating process and cooling process. The tensile and yield strength of bending beam of aluminum alloy casting which is processed by aging treatment are shown in figure 8(a), (b).

Figure 8. Tensile and yield strength of bending beam of aluminum alloy casting.

In fig. 8, the distribution of tensile strength is similar to the temperature field in the cooling process. But the values of tensile strength are just the opposite. Its maximum tensile strength is approximately 355MPa and located at the edge of casting, and the minimum value is approximately 338MPa and
located at the inside of casting. It is assumed that there exist some corresponding relationships between the tensile strength and the temperature field and the tensile strength is improved through aging treatment. As such, the distribution of yield strength is similar to tensile strength and the values of yield strength are approximately limited on range from 283MPa to 300MPa.

5 Conclusions
By the advanced simulation platform of casting and heat treatment, the whole process of aluminum alloy cast by low-pressure and heat treatment are simulated and all forming factors in various stages of the whole process are analyzed. The conclusions are obtained as follows:

1. In filling process, all the sudden change in the flow direction of the molten metal, the occurrence of turbulent flow and the more heat loss contribute significantly to the obvious temperature drop, and the temperature at the final filling region is significantly less than the other regions;

2. In solidification process, the distribution of shrinkage porosity and shrinkage cavity caused by filling and solidification process has been predicted; in the late stage of solidification, the stress distribution is similar to the distribution of shrinkage porosity and shrinkage cavity. Meanwhile, the stress and shrinkage properties are all affected by the temperature changing with time in the solidification process;

3. In heating process, the absolute values of temperature and X-displacement are big in the end and small in the middle; in cooling process, the absolute values of temperature are big in the middle and small in the end. On the contrary, the absolute values of X-displacement are big in the end and small in the middle. There exist some corresponding relationships between the tensile strength and the temperature field and the tensile strength is improved through aging treatment. As such, the distribution of yield strength is similar to tensile strength and the values of yield strength are approximately limited on range from 283MPa to 300MPa.

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