Heat transfer and stress evolution behaviours of an aluminium alloy low pressure shell casting

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Abstract. Considering the solidification, demoulding and heat treatment processes in low pressure casting, relatively complete processes of an aluminium alloy shell casting are simulated to investigate the heat transfer feature and stress behaviours variation of casting in each multi-processes stage. FDM is used to discrete thermal conduction model when studying the heat transfer process, while FEM is adopted to solve the elastic-plastic model when studying the stress behaviour variation. When matching the two models, we map the finite difference mesh to finite element mesh. Three different temperature conditions, namely 300\(^\circ\)C, 400\(^\circ\)C and 500\(^\circ\)C, are simulated when we research the influence of demoulding temperature on stress behaviour. The simulation results demonstrate that the higher demoulding temperature is, the greater casting deformation and the smaller stress value are. The final casting stress status and the initial heat treatment temperature have a different relationship as for different parts of casting.

1. Introduction
Aluminium alloys have been utilized extensively in the automotive, aircraft and vessel etc. because of their superior mechanical properties. ZL101A is one of the commonly used aluminium alloy. It has good casting capability which can be strengthened by heat treatment. This kind of material is widely used in Shell parts. Stress of the casting is extremely easy to be produced and even the deformation and crack will appear when the thickness of casting is uneven. And as a means to improve the performance of aluminium alloy shell, the subsequent heat treatment also can lead to the emergence of the thermal stress. Even if the process of treatment is not proper, casting may still be discarded. So there are many scholars separately studying the stress distribution in the casting process \(^{[1-4]}\) or in the heat treatment process \(^{[5-12]}\), but few of them researching the stress in the whole process by combining the casting process with heat treatment process. Therefore the paper attempts to study the influence on the stress distribution and deformation in different initial heat treatment temperature or demoulding temperature. Firstly, the numerical simulation of solidification will be carried out for aluminium alloy shell casting; Secondly, when the temperature decreases to 500, 400, or 300\(^\circ\)C, the demoulding stress will be calculated; Lastly, the numerical simulation of heat treatment will be made at initial temperature of 500, 400, or 300\(^\circ\)C.

2. Mathematical model

2.1. Heat transfer model
The heat transfer model solves 3D transient conduction equation, using Finite difference method.

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\[
\rho c \frac{\partial T}{\partial t} = \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right)
\]  
\tag{1}

Where \( \rho \) is the density, \( c \) is the specific heat capacity, \( \lambda \) is the thermal conductivity, \( T \) is the temperature, \( t \) is the time, \( x, y \) and \( z \) are the coordinates.

2.2. Stress evolution model
Thermal elastic-plastic model of the stress model can be divided into elastic stage and plastic stage. Material complies with the generalized Hooke’s law at elastic stage and the expression is Eq2. But the state of strain depends on the paths of loading at plastic stage, and then it only builds the relationship between stress increment and strain increment at instantaneous state, namely the increment theory and the expression of Eq3. In practical engineering applications, usually we use the bilinear model instead of the nonlinear model for plastic stage in order to simplify the thermal elastic-plastic model for disposing plastic state of complex material. Then \( C^{\text{op}} \) can be represented as Eq4. Yield criterion is used to determine whether the material turn into a plastic state from an elastic state. The expression is Eq5.

\[
\sigma = C^e \varepsilon
\]  
\tag{2}

\[
d\sigma = C^{\text{op}} d\varepsilon
\]  
\tag{3}

\[
C^{\text{op}} = m C^e + (1 - m) C^p
\]  
\tag{4}

\[
\bar{\sigma} = \frac{1}{\sqrt{2}} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]
\]  
\tag{5}

Where \( \sigma \) is the stress, \( \varepsilon \) is the strain, \( C^e \) is the constitutive tensor of elastic, \( d\sigma \) is stress increment, \( d\varepsilon \) is strain increment, \( C^{\text{op}} \) is constitutive forth order tensor of elastic-plastic. Eq3 contains an assumption, a physical parameters and mechanical parameters are very small with the change of temperature and time in an incremental step, and it can be negligible. Where \( C^p \) is constitutive tensor of plastic, \( \bar{\sigma} \) is equivalent stress, \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are the principal stresses.

3. Simulation process
3.1. Casting model
Figure 1 shows the 3D model of the casting. The green part is casting and the blue part is casting system. The grid of the model is shown in b). The process is low pressure casting. The thickness of the shell casting is in uneven distribution. The stress produced in casting and heat treatment can bring about deformation. It has a great influence on product reliability.
3.2. Material parameters

Figure 2. Thermal physical parameters of ZL101A.

Figure 2 shows the thermal physical parameters of ZL101A. Density, specific heat, thermal condition and heat transfer coefficient are shown in a), b), c) and d) respectively. These parameters are calculated by J-Matpro\textsuperscript{[13]} or obtained by reviewing literature \textsuperscript{[14]}. The mould is metal and the density is 7.86g/cm\textsuperscript{3}, the thermal conduction is 58.6w/(m \cdot °C), the specific heat is 518.8 J/(Kg \cdot °C).

3.3. Process parameters
Figure 3 shows the three process curves of heat treatment. When the temperature of casting decreases to 500 °C, 400 °C, 300 °C after solidification, demoulding will be done, then the casting will be raised to 540 °C with the heating rate of 101 °C/h and quenching in the water of 80 °C after thermal insulation at 540 °C for 8-10h. This article simulates the process of filling solidification, demoulding and heat treatment by FDM, calculates the stress of the whole process by FEM, and the influence on the performance in different demoulding temperature is analyzed.

4. Results and discussion

4.1. Solidification stage

Figure 4 shows the temperature, stress and strain after solidification. The temperature at the inlet is the highest and the temperature at the top of the thin-wall casting part is the lowest (Figure 4 a)). On the whole, the temperature of the upper casting is lower than temperature of the runner on the bottom. The reason is that its way of casting is low pressure casting. The equivalent stress distribution of solidification as shown in Figure 4 b) is about from 0Mpa to 280Mpa, and most of the casting stress is 150Mpa. But stress concentration would be appeared at some corners; on the contrary, the stress of thick parts is very small. The equivalent strain distribution is very uneven, this means that the castings will be out of shape, which has a great influence on the casting quality. If we only consider the heat treatment stress and ignore the solidification stress, the final prediction accuracy of the performance would be greatly reduced.

4.2. Stress and strain curves
In order to analyze stress and strain in the whole process, two points (Figure 16) on the casting are taken to draw curves. The curves of the whole process are too long, so here the whole curves of stress and strain are divided into three parts: 0-100s (Figure 6 a) and d)), 100s-4000s (Figure 6 b) and e)), 4000s-47000s (Figure 6 c) and f)). Point A is at the corner of casting while point B is at the centre of the runner.

The residual stress and strain distribution of solidification are uneven, such the two points (Figure 6 a) and d)). If the residual stress of solidification process is not considered, then the initial stress state would be assumed to be uniform and zero for heat treatment. It has a great influence on the stress distribution for the casting.

For demoulding stage, the stress and strain will be mutant when demoulding, such as Figure 6 a) and d). The stress and strain of point A and point B have different trends at different demoulding temperature. For point A, the stress and strain have minimal values at temperature demoulding of 400°C. But the minimal stress and strain of point B appear at demoulding temperature of 300°C. The main reason is that the point A is in the thin wall while the point B is in the sprue center of thick wall.

For heating stage, the stress increase and stress of 500 demoulding temperature is smallest at point A. But the stess of 400 demoulding temperature is smallest at point B (Figure 6 b)). The strain of point A is difference for the three kinds of condition, but that of point B is approximate equality for the three kinds of condition (Figure 6 e)). The reason is that the point B is at the centre of the runner, the stress and strain is very little, but the point A is far from the centre.

For the cooling stage, the stress of both points all increase first and then reduce, last approximately remain the constant. But the strain of two points is different. The strain of point A increase first and then reduce, however, the strain of point B reduce first and then increase. The reason is that the main factors influencing the value of stress and strain are cooling rate and temperature. The cooling rate is very great and then it reduces. For the thin wall, the influence of cooling rate on the stress and strain is dominant in the beginning. The influence of temperature on them is dominant with the loss of the cooling rate, so the values increase first and then reduce. For the thick wall, the cooling rate is not very great, and it will be postponed relative to that of thin wall. The influence of temperature on strain is dominant in the beginning, so the values reduce first and then increase.
Figure 6. Stress and strain curves of two points. a) stress curves from 0-100s, b) stress curves from 100-40000s, c) stress curves from 40000-47000s, d) strain curves from 0-100s, e) strain curves from 100-40000s, f) strain curves from 100-40000s.

Table 1. The values of stress and strain at different stage.
Table 1 shows the values of stress and strain for the two points at different stage. For the same demoulding temperature, the stress and strain of point A are greater than that of point B before demoulding, and the decrement of stress and strain after demoulding is also greater than that of point B. For the same point, there are different rules for thick wall and thin wall casting. The higher the demoulding temperature is, the greater the stress is and the smaller the strain is for thick wall after demoulding(point B). But the stress and strain is smallest when the demoulding temperature is 400 for thin wall (point A). At last, the stress at the demoulding temperature of 500°C has the minimal value. Bnd the strain at the demoulding temperature of 400 has the minimal value. For the point B, the final casting stress and strain at the demoulding temperature of 500°C has the minimal value.

5. Conclusion
The solidific ation, demoulding, and heat treatment of an aluminium alloy shell have been investigated in this paper. The simulation results at three different demoulding temperatures are compared and the following conclusions can be drawn:
1) The higher the demoulding temperature is, the smaller the whole stress of casting before demoulding is, but the bigger the whole stress of casting after demoulding is.
2) For the same point, The higher the demoulding temperature is, the greater the stress is and the smaller the strain is for thick wall after demoulding.
3) the stress at the demoulding temperature of 500°C has the minimal value, Bnd the strain at the demoulding temperature of 400 has the minimal value. For the point B, the final casting stress and strain at the demoulding temperature of 500°C has the minimal value

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