Formation law and criterion of nebulous macroscopic segregation in ZL205A alloy castings

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Abstract: The appearance of macroscopic segregation in ZL205A alloy castings bears a super resemblance to the appearance of shrinkage porosity, and the chemical composition of the segregation is Al_2Cu whose microstructure is in the form of dentrite or skeleton crystal. According to the characteristic of nebulous segregation, the formation process could be divided into two steps by the eutectic temperature of Al_2Cu. Then a criterion for each of the two steps is brought forward on the basis of the shrinkage porosity criterion of low pressure casting.

Keywords: ZL205A alloy; macroscopic segregation; formation law; criterion
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With the rapid development of aeronautics and aerospace technology, the strength requirement for material gets higher and higher. The deformable aluminum alloy could satisfy the strength requirement, but compared to cast aluminum alloys, the requirement for equipment and dies is also higher and working procedure is lengthy and complex, resulting in longer production cycle and higher production cost. Developing new high strength cast aluminum alloys to replace parts of deformable aluminum alloy has been the international research focal point. Many such cast aluminum alloys had been developed, such as A-U5GT (France), KO-1 (USA), BAЛ10 (USSR) and so on [1-2]. ZL205A alloy with tensile strength reaching 510 MPa had been invented by China in the 1970s, and it has been popular with aeronautics, aerospace and weapon designers because it is currently one of the highest strength cast aluminum alloys available.

ZL205A alloy belongs to the Al-Cu cast alloy system, and its castability is poor due to mushy solidification mode. Consequently, its tendency for segregation, shrinkage and hot crack is high in castings at the temperature ranging from 633℃ to 544℃, which limits its development and application [3-6]. The linear segregation [7], punctate segregation[8], zonal segregation and nebulous segregation were discovered in ZL205A alloy large castings produced by low pressure casting.

It has been over 30 years since the ZL205A alloy was developed, but less than 10 years since it was used in large castings with diameter over 2 meters. There was no reference on ZL205A alloy segregation, so this casting defect became a momentous problem to be solved. The formation law and criterion of nebulous segregation in ZL205A alloy large castings have been investigated in this study to offer ideas and understanding for solving the defect, which would have a great value in optimizing casting technique, improving casting yield, shortening production cycle, reducing production cost, and facilitating its application in the aeronautics, aerospace and weapon domains.

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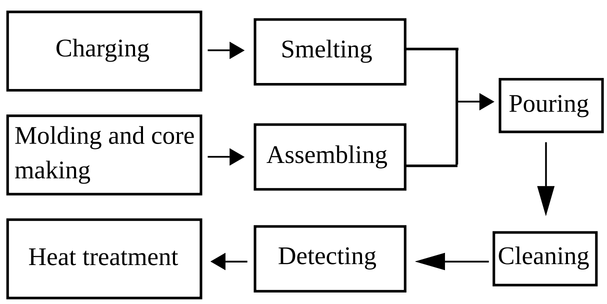
1 Experiment process

1.1 Raw material and experimental procedures

The chemical composition of ZL205A is complex, containing Cu, Mn, Ti, V, Cd, Zr and B, aggregately seven alloying elements, as shown in Table 1.

The applied technological process for ZL205A alloy experimental castings was as follows:



(1) Charging: The raw materials were prepared according to the calculation of consumption amount. Al is the first grade of industrial aluminum with a purity of 99.99%; Cu, Mn, Zr, V, Ti and B elements are added in the form of aluminum matrix masteralloys; and Cd is the second industrial grade with a purity of ≤ 99.99%.

Table 1 The chemical composition of ZL205A alloy, wt.%

Cu	Mn	Ti	Cd	V	Zr	B	Al
4.6–5.3	0.3–0.5	0.15–0.35	0.15–0.25	0.05–0.3	0.05–0.2	0.005–0.06	balance

(2) Smelting: The metal was smelted in a 2-ton electric crucible furnace (ECF). The Al-Mn, Al-Zr, Al-V alloys and aluminum ingots were charged into the ECF at room temperature, while the Al-Cu alloy was added at the temperature between 715 ℃ and 725 ℃, and Al-Ti-B between 740 ℃ and 750 ℃. After these added, the molten metal was stirred for five minutes, and then refined for degassing with TiO_2 and Cl_6C_2 refining agents. Finally, Cd block was charged in at the temperature between 720 ℃ and 730 ℃, followed by another 5-minute mixing.

(3) Molding and core making: Furan resin bonded sand was applied to the mold and core.

(4) Pouring: DY600 digital low pressure casting machine was used for pouring, with the liquid rising speed of 60 mm/s, the cavity filling speed 15 mm/s, and the holding time 580 s.

(5) Cleaning: The sand, risers and runners were removed from casting, and simple machining was performed on the casting surface.

(6) Detecting: XXQ (H) 2005 digital x-ray flaw detector was used to detect the casting.

(7) Heat treatment: The heat treating technique was T6, consisting of solution treatment at 540 ℃ for 18 h, then quenching in water at 40 ℃—80 ℃, and ageing at 170 ℃ for about 3.5 h followed by air cooling.

1.2 Detection results

There were two kinds of nebulous segregation appearance in Fig.1, acquired from ZL205A alloy large castings by XXQ (H) 2005 digital x-ray flaw detector. The appearance was like cloud and mist and very similar to the appearance of shrinkage porosity though the color was opposite in the x-ray negative films: the segregation was white while the shrinkage porosity was black.

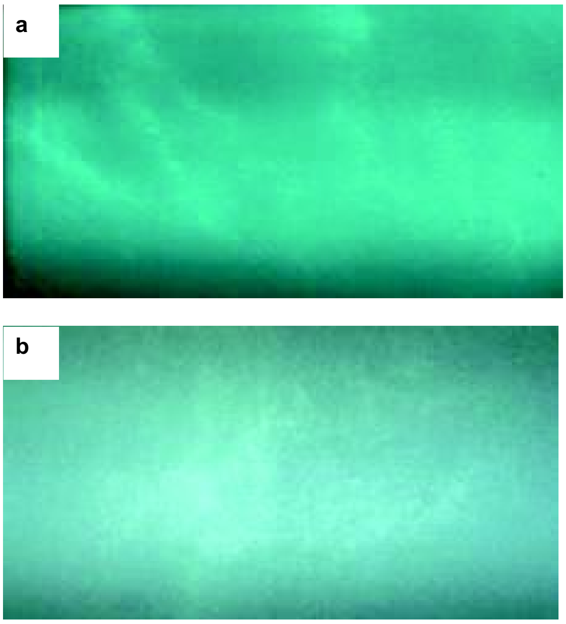
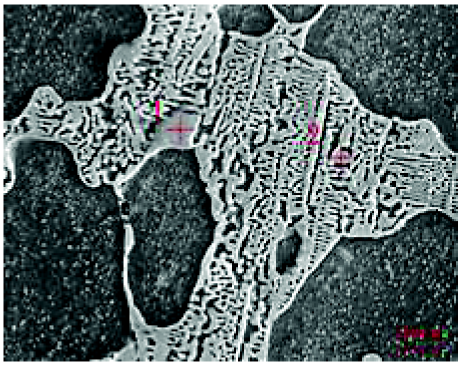


Fig.1 The macroscopic figure of ZL205A alloy nebulous segregation

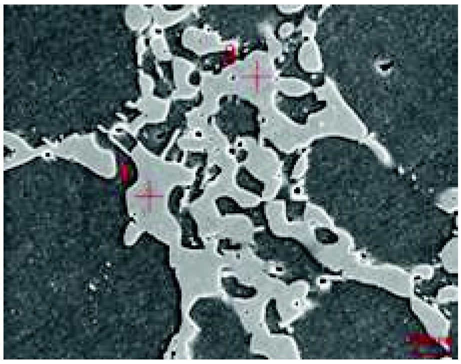
1.3 Microstructure and chemical composition of nebulous segregation

The microstructure of nebulous segregation in the ZL205A alloy casting samples was in the form of dentrite or skeleton crystal, which was observed with S-3400N SEM (shown in Fig.2). Then four regions marked by "+" sign were chosen to analyze the composition of segregation with energy dispersive x-ray analysis (EDX). The results are shown in Fig.3. The nebulous segregation are made up of Al and Cu elements whose mol ratio are $\frac{66.33}{33.67}$, $\frac{68.45}{31.55}$, $\frac{68.53}{31.47}$ and $\frac{66.97}{33.03}$, close to 2:1.

According to Zhang W Q's research, the chemical composition of nebulous segregation should be Al_2Cu, a kind of eutectic [9]. The eutectic temperature of Al_2Cu is 548℃, which can be obtained from the Al-Cu binary alloy phase diagram.



(a)The dentrite crystal



(b)The skeleton crystal

Fig.2 The microstructure of nebulous segregation in ZL205A alloy casting

2 The formation law

There are three representative characteristics about nebulous segregation in ZL205A alloy castings:

(1) The appearance is very similar to that of shrinkage porosity;

(2) The region where the segregation forms seems to be stochastic, but the probability is higher where the shrinkage forms;

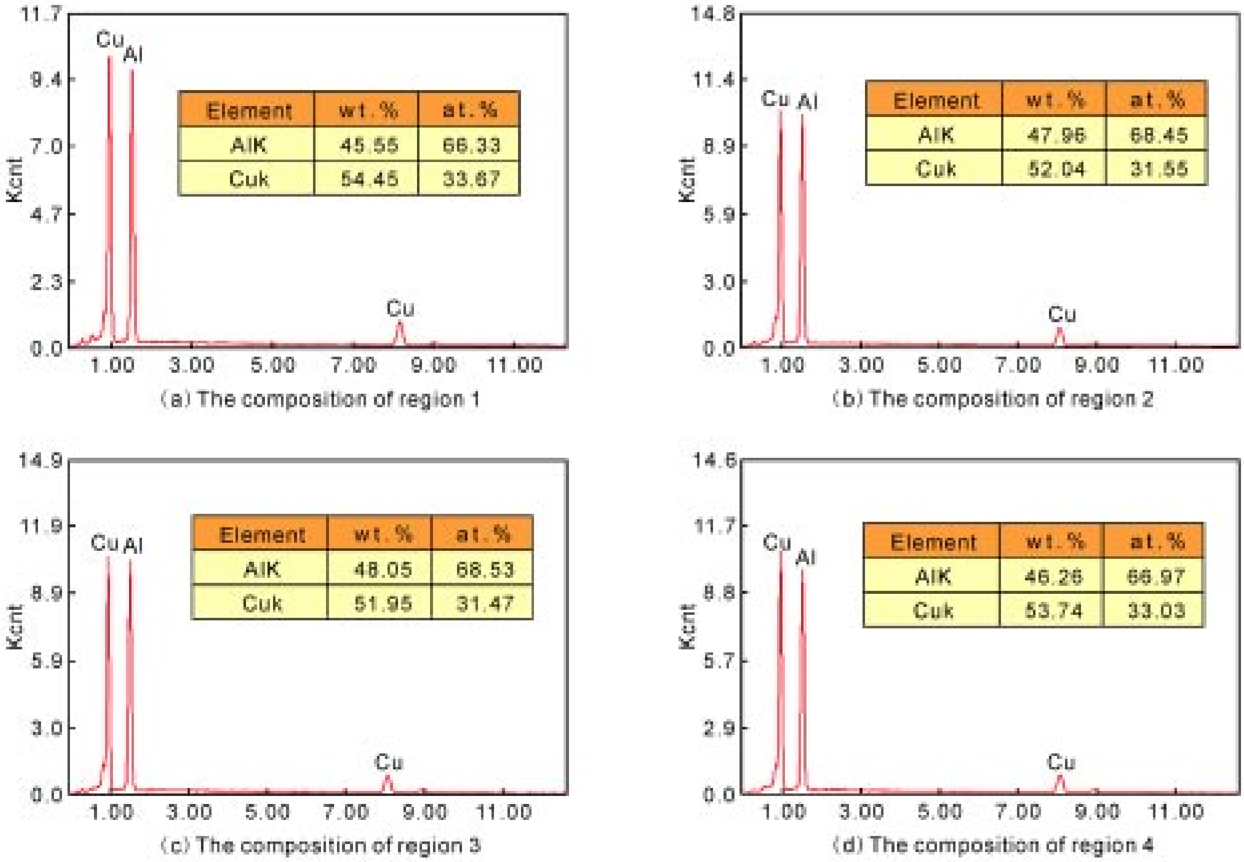


Fig.3 The composition of nebulous segregation in ZL205A alloy castings

(3) The segregation is Al_2Cu eutectic with eutectic temperature of 548℃.

It can be inferred from such characteristics that the formation process of nebulous segregation in ZL205A alloy castings be divided into two steps: First, the shrinkage porosity forms due to liquid shrinkage and solidification shrinkage in local hot spots at above 548℃; Second, the liquid enriching Cu based on Scheil formula feeds into the nearby shrinkage porosity area under a high pressure at a temperature slightly above or close to 548 ℃, then eutectic reaction takes place to give birth of Al_2Cu at 548℃, resulting in the nebulous segregation in ZL205A alloy castings.

Nebulous segregation cannot occur in ZL205A alloy castings in the following three situations:

(1)The shrinkage porosity does not form during solidification;

(2)The shrinkage porosity is formed during solidification, but there is no liquid to supply, or the liquid cannot flow into the shrinkage porosity area because the pressure cannot conquer flow resistance due to high loss of flow pressure, so the shrinkage porosity will exist through to room temperature;

(3) The shrinkage porosity is formed during solidification and the liquid is able to flow into the shrinkage porosity area, but the liquid solidifies without eutectic reaction if the temperature is far above 548 ℃ and no significant Cu enrichment exists, so the fed metal in this area ends up with matrix structure and becomes a nice part of casting.

Therefore, the nebulous segregation forms only when both of the two steps' conditions are satisfied.

3 The criterion

(1) The criterion of first step of nebulous segregation

The feeding process of the alloys with broad freezing temperature range can be considered as interdentritic flow of the liquid [10], which can be described with Darcy's law:

$$\boldsymbol{v}_0 = \frac{k}{\eta f_i} \triangle p \qquad (1)$$

where v_0 is flow rate, k is the permeability, f_i is the liquid rate of the mesh zone, η is viscosity, and ΔP is pressure gradient.

The primary reason for the interdentritic liquid flow is solidification shrinkage. The velocity component caused by solidification shrinkage is

$$\boldsymbol{v}_0 = \frac{R}{G} \beta \qquad (2)$$

where β is solidification shrinkage ratio of the metal, G is temperature gradient, and R is cooling rate. Equation (3) can be obtained by combining equations (1) and (2):

$$\frac{R}{G} \beta = \frac{k}{\eta f_i} \triangle p \qquad (3)$$

$\triangle p$ can be given by $\triangle p = \triangle P / \triangle x$, $\triangle x = \triangle T/G$, where $\triangle P$ is pressure difference over solidification feeding distance, and $\triangle T$ is the difference in temperature.

Then equation (3) becomes

$$\frac{G}{\sqrt{R/\triangle P}} = \sqrt{\frac{\beta \eta f_i \Delta T}{k}} \qquad (4)$$

where β, η and k are constants which are determined by the properties of the alloy, while f_1 and ΔT are related to specific location in dentrites. Considering practical solidification process, the liquid will stop flowing when the solid rate (fraction) in the mushy zone reaches its critical value f_{sc}. Thus, the solid rate point f_{sc} can be chosen as the point of dentrite, and accordingly the ΔT can be given by

$$\Delta T = T_1 - f_{sc}\Delta T_0 \qquad (5)$$

where T_1 is liquidus temperature of the alloy, ΔT_0 is the range of solidification temperature. In this case, the right side of equation (4) is a definite value which can be ordered equaling to K_c, and G and R on the left of equation (4) are the temperature gradient G_{sc} and the cooling rate R_{sc} at the moment in the casting, respectively.

If $P_{sc} < \Delta P$, the liquid will stop flowing and shrinkage porosity will form in castings. So the formula is

$$\frac{G_{sc}}{\sqrt{R_{sc}/P_{SC}}} < K_c \qquad (6)$$

Under the condition of low pressure casting,

$$P_{sc} = P_{atm} + P_{LPDC} - \rho_l gh \qquad (7)$$

where ρ_l is the density of the metal liquid, g the acceleration of gravity, h the height of discretional point in castings, P_{atm} the atmospheric pressure, and P_{LPDC} the pressure of low pressure casting.

When combined with equation (7), the equation (6) will become the criterion of shrinkage porosity under the condition of low pressure casting [11]. Considering the condition of temperature

$$T \in (548\ ℃ + T_\alpha, T_\beta) \qquad (8)$$

where $T_\alpha > 0$, T_3 is the temperature at which the solid shrinkage is greater than liquid shrinkage and solidification shrinkage. The equation (6) will become the criterion of the first step of nebulous segregation formation under the condition of low pressure casting in ZL205A alloy castings when combining with equations (7) and (8).

(2) The criterion of second step of nebulous segregation

There is pressurization period in low pressure casting process, so P_{LPDC} will becomes P_{LPDC}*, and the equation (7) will become

$$P_{sc}^* = P_{atm} + P_{LPDC}^* + \rho_l gh \qquad (9)$$

If $P_{LPDC}^* > \Delta P$, the pressure can overcome the flow resistance, and the residual liquid will feed the shrinkage porosity area which formed in the first step. Thus, the condition is

$$\frac{G_{sc}}{\sqrt{R_{sc}/P_{SC}^*}} > K_c \qquad (10)$$

For eutectic reaction, temperature must meet the condition below

$$T \in (548℃,\ 548℃ + T_\gamma) \qquad (11)$$

where T_γ is a constant and $\lim T_\gamma = 0$.

When combining with equations (9) and (11), the equation (10) will become the criterion of the second step of nebulous segregation under the condition of low pressure casting in ZL205A alloy castings.

The parameters of solidification are not independent from each other, and a single parameter cannot reflect the formation mechanism of casting defect in nature. The shrinkage porosity criterion on aluminum alloy is still in dispute. Therefore, the two-step criterion of nebulous segregation in ZL205A alloy castings which is derived from shrinkage porosity criterion has its limitations, and may be used only for prediction on the trend of nebulous segregation formation.

4 Conclusions

(1) The microstructure of nebulous segregation in ZL205A alloy is in the form of dentrite or skeleton crystal, and composition of the segregation is Al_2Cu.

(2) The formation process can be divided into two steps: First, the shrinkage porosity forms in hot spots above 548 ℃; Second, the liquid enriched with Cu element based on Scheil formula feeds the nearby shrinkage porosity area under a high pressure at a temperature close to 548 ℃, and then eutectic reaction takes place to precipitate the Al_2Cu phase at 548 ℃, resulting in the nebulous segregation in ZL205A alloy castings.

(3) The two-steps criterion of nebulous segregation in ZL205A alloy castings has some limitations, and may be used only to forecast the trend of nebulous segregation.

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