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Microstructure and Mechanical Properties of ZL205A Aluminum Alloy Produced by Squeeze Casting after Heat Treatment

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Abstract: In this paper, ZL205A (AlCu5Mn alloy) castings were prepared by squeeze casting. The effects of solution and ageing treatment on the microstructure and mechanical properties of ZL205A castings were studied by metallography, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and mechanical properties tests. The results showed that most of the \(\theta(Al_2Cu)\) and \(T(Al_12CuMn_2)\) phases in squeeze-cast ZL205A dissolved into the \(\alpha(Al)\) matrix after solution treatment for 15 h. The fine precipitates gradually increased with the ageing time. The ultimate tensile strength of the specimen aged for 6 h was the highest of 467 MPa and the elongation was up to 15.1%, showing good comprehensive mechanical properties.

Keywords: squeeze casting; ZL205A aluminum alloy; mechanical properties; heat treatment; microstructure

1. Introduction

Casting aluminum alloy ZL205A, which is named by Chinese national norm, is a typical high toughness and heat resistant casting Al-Cu-based alloy [1]. It is widely used in the fields of aerospace, aircraft and automobile manufacturing due to high tensile strength, good corrosion resistance, good processability [2,3].

However, the castability of the Al-Cu alloy is comparatively poor, compared with the Al-Si alloy [4]. With about 5% content of Cu added as a primary strengthening element, the ZL205A alloy has a wide crystallization temperature range and strong tendency to undergo microshrinking, and to exhibit hot cracks and cavities. A certain amount of eutectic phase and \(\theta(Al_2Cu)\) intermetallics will be produced in the as-cast microstructure of the ZL205A alloy [3]. This will cause the problems of coarse grain, embrittlement, grain boundary segregation, and poor casting performance [5]. The mechanical properties of Al-Cu casting alloys are greatly influenced by the morphology structure, distribution, grain size and “overburned” phenomenon of intragranular precipitated phase, dispersed precipitated phase and undissolved solution phase. It has a wide range of crystallization temperature, and the casting stress in the production process makes the hot spot of castings prone to hot cracking.

Squeeze casting is a precision-forming method that achieves castings by facilitating the liquid metal solidification under high pressure. Using squeeze casting process to produce ZL205A alloy castings can improve the density of the alloy structure, refine the grains, improve the toughness and strength of the casting, and make up for the shortcomings of the poor casting properties of the ZL205A alloy [6–8]. Because the solidification and crystallization process is completed under the non-equilibrium condition, the content of solute element copper precipitated into \(\alpha(Al)\) phase is very small, and the coarse eutectic formed by Cu element is distributed at the grain boundary of the casting structure [7].
Under the condition of squeeze casting, the as-cast castings do not fully reflect the high-strength characteristics of the Al-Cu alloy, which cannot meet the requirements of squeeze casting parts.

Heat treatment is an important factor affecting the structure and properties of Al-Cu alloys, and an important way to strengthen and toughen Al-Cu alloys [9,10]. The ZL205A alloy is a typical heat-treatment-strengthened alloy [11,12]. Under the extrusion pressure of 50 MPa, the microstructure of the alloy processed by direct squeeze casting after T4 solution treatment is consisted of fine equiaxed α(Al) grains with uniform size, and a relatively large amount of dispersed phase [13]. With the increase in solution time, the hardness increases gradually and reaches the peak value after solution for 3–5 h. After artificial ageing treatment, the tensile strength and yield strength of vertical continuous casting ZL205A increased with the ageing time and temperature. After ageing at 180 °C for 8 h, the tensile strength reached 406 MPa [14].

Therefore, in order to give full play to the potential of Al-Cu alloys and obtain castings with good quality and mechanical properties, it is very important to heat treat the squeeze castings and investigate the responsible formation mechanism. In the present paper, the influence of solution treatment and ageing treatment on the microstructure and mechanical properties of ZL205A alloy casting by squeeze casting process are studied. The strengthening and toughening mechanisms of squeeze casting ZL205A alloy are also discussed.

2. Materials and Methods

2.1. Materials

The material studied in this paper is the ZL205A alloy. The nominal chemical composition (wt.%) of ZL205A alloys is Al-5Cu-Mn. After squeeze casting, the real compositions (Table 1) of ingot were measured with inductively coupled plasma atomic emission spectroscopy (ICP-AES). The shape of die cavity is spiral, which is used to form the squeeze casting parts with a single process length. The indirect squeeze casting is adopted in the design of squeeze casting die. The pressure was applied to the alloy melt in the pressure chamber, which could produce parts with complex shape and large wall thickness difference, and met the requirements of high performance.

|        | Cu   | Mn | Ti  | Fe  | Al     |
|--------|------|----|-----|-----|--------|
|        | 4.14 | 0.38 | 0.26 | 0.24 | Balance |

The weighed ZL205A ingot was melted in a resistance furnace. After the alloy was completely melted, it was heated up to 730 °C and held for 10 min. It was refined with dry C2C16 degassing (0.2% by mass) and mixed evenly. Then, the alloy liquid was left to remove the slag and was ready to be poured.

The squeeze casting die was preheated by electric heating rod. When the die was preheated to 150 °C, the die cavity and the surface of the pressing chamber were evenly coated by the lubricant of graphite and engine oil. Then, the prepared alloy liquid was poured into the pressing chamber and squeeze casting commenced.

The macrograph castings formed by squeeze casting with two different extrusion pressures of 30 MPa or 60 MPa are shown in Figure 1. The spiral line parts of the samples were completely filled. There were cold insulation defects in the center of the sample, as indicated by the red arrow in Figure 1. When the squeeze pressure was 30 MPa, the spiral line part of the sample broke and the surface was relatively rough. When the squeeze pressure rose to 60 MPa, the surface became smooth without obvious macro defects.
Figure 1. Macrographs of ZL205A alloy samples produced by squeeze casting with different extrusion pressures: (a) 30 MPa; (b) 60 MPa.

2.2. Heat Treatment and Characterization

The sample obtained by squeeze casting with 60 MPa squeeze pressure was cut into specimens of 5 mm × 12 mm × 35 mm, which were prepared for heat treatment. Table 2 shows the heat treatment parameters. The samples were treated with solution treatment at 538 °C, respectively, then quenched in water after being taken out from a furnace. Ageing treatment was carried out on the specimen after solution treatment at 538 °C for 15 h. The specimens were cooled naturally with the furnace after heat preservation.

Table 2. Ageing treatment process of specimens.

| Solution Treatment | Ageing Treatment |
|--------------------|------------------|
| T/° C               | t/h              |
| 538 °C × 15 h       | 155 °C           |
|                     | 4 h, 6 h, 8 h    |

The metallographic specimens of ZL205A after heat treatment were cold-inlaid with epoxy resin, and then the inlaid specimens were rough ground, fine ground and mechanically polished. Then, the Keller etchant with the volume ratio of HNO₃:HCl:HF:H₂O = 2.5:1.5:1:95 was used for 20 s, then washed with alcohol and dried under the blower. The microstructure, element composition and phase structure of the specimens after solution and ageing treatment were observed and analyzed by optical microscope (OM), scanning electron microscope (SEM, with energy dispersive spectrum (EDS) attached) and X-ray diffractometer. The D8 Advanced X-ray diffractometer of Germany BRUKER Company was used for phase composition analysis. The ZL205A alloy sample was processed from the central block of the squeeze casting into tensile specimen as shown in Figure 2. The thickness of the tensile specimen was 0.8 mm. All data were taken from at least three separated measurements. The ultimate tensile strength (UTS, MPa), yield strength (YS, MPa) and elongation (EL, %) of the alloy under different heat treatment processes were obtained after tensile tests.
There are equiaxed grains in the as-cast microstructure. The grain boundary is clear, but point A and point B is the eutectic of point B. Point C is α phase, and there are also α(Al) matrix phase. From the X-ray spectrum shown in Figure 6, it can be seen that the as-cast specimen is mainly composed of α(Al) phase, and there are also θ(Al2Cu) and T(Al12CuMn2) phases. Therefore, the continuous network structure of point A and point B is the eutectic of θ(Al2Cu) phase and T(Al12CuMn2) phase. This is consistent with the solidification process of the Al-Cu-Mn alloy ternary phase diagram. The segregated phases are formed at the grain boundaries. Because there are many alloying elements in ZL205A, a large number of eutectic distribute discontinuously at the α(Al) grain boundary. These eutectic phases are observed as shown in Figure 4a. The existence of these grain boundary phases seriously split the matrix continuity, which greatly reduces the properties of the alloy. Therefore, heat treatment must also be carried out to modify the microstructures.

3. Results

The as-cast microstructure of ZL205A alloy by squeeze casting is mainly composed of a matrix α(Al) phase, and a grain boundary secondary phase, as shown in Figure 3. There are equiaxed grains in the as-cast microstructure. The grain boundary is clear, but the secondary phase distribution along the grain boundary is discontinuous.

![Figure 3. Optical micrograph of squeeze-cast ZL205A.](image)

Scanning electron microscopy micrographs of squeeze-cast ZL205A before and after solution treatment are shown in Figure 4. The morphology of the secondary phase is a continuous network structure, as shown in Figure 4a. The energy spectrum analysis of points A and B in the network structure at the grain boundary of ZL205A as-cast is carried out as shown in Figure 5. The results show that the grain boundary is mainly composed of Al and Cu elements, and there is a certain amount of Mn element in the position of point B. Point C is α(Al) matrix phase. From the X-ray spectrum shown in Figure 6, it can be seen that the as-cast specimen is mainly composed of α(Al) phase, and there are also θ(Al2Cu) and T(Al12CuMn2) phases. Therefore, the continuous network structure of point A and point B is the eutectic of θ(Al2Cu) phase and T(Al12CuMn2) phase. This is consistent with the solidification process of the Al-Cu-Mn alloy ternary phase diagram. The segregated phases are formed at the grain boundaries. Because there are many alloying elements in ZL205A, a large number of eutectic distribute discontinuously at the α(Al) grain boundary. These eutectic phases are observed as shown in Figure 4a. The existence of these grain boundary phases seriously split the matrix continuity, which greatly reduces the properties of the alloy. Therefore, heat treatment must also be carried out to modify the microstructures.
Figure 4. Scanning electron microscopy micrographs of squeeze-cast ZL205A: (a) as-cast; (b~d) after solution treatment at 538 °C, (b) 6 h; (c) 15 h; (d) 17 h.

Figure 5. Cont.
Figure 5. The phase components detected by energy dispersive spectrometer: (a) Point A (Al$_2$Cu); (b) Point B (Al$_{12}$CuMn$_2$); (c) Point C α(Al).

Figure 6. XRD spectrum of squeeze-cast ZL205A.
After solution treatment at 538 °C for 6 h, the continuous network distribution of precipitates at grain boundaries are reduced obviously. The precipitated phase is transformed into a dispersed fine, short precipitated phase, which avoids the split of precipitated phase relative to α(Al) matrix, and greatly improves the tensile strength of castings. With the increase in solution time, the amount of the secondary phase at the grain boundary decreases, and the Cu element gradually dissolves into the solution. However, there is still a part of the undissolved secondary phase distributed discontinuously at the grain boundary, as shown in Figure 4b.

When the solution treatment is increased to 15 h, the θ(Al12Cu) phase and T(Al12CuMn2) phase in the alloy are mostly dissolved in α(Al), as shown in Figure 4c, and the amount of undissolved secondary phase is very small. The eutectic network structure disappears at the grain boundary and the grain boundary becomes fine and smooth. The residual secondary phase is distributed along the grain boundary in the form of granular dispersion, and the effect of solution strengthening is the most obvious. Therefore, the mechanical properties of castings after solution treatment for 15 h are expected significantly higher than those after solution treatment for 6 h. However, with the further increase in solution time to 17 h, the grains begin to grow and coarsen in the casting as shown in Figure 4d.

The changes in the trends of the stress–strain curves of squeeze cast ZL205A specimens under different solution time treatments are similar, as shown in Figure 7. The elastic deformation stages are similar after different solution time treatment. At the stage of elastic-plastic deformation, there is no obvious yield phenomenon. The tensile curves conform with the typical fracture characteristics of aluminum alloy. The ultimate tensile strength of as-cast is 175 MPa and the elongation is about 4.7%. After solution treatment, the tensile strength and elongation of ZL205A alloy castings are obviously improved. After 15 h solution treatment, the ultimate tensile strength can reach the highest value of 381 MPa, which is 118% higher than that of as-cast. The elongation of 15 h solution specimen reaches 16.1%, which is much higher than that of as-cast. With the solution time increases to 17 h, the ultimate tensile strength and elongation decrease obviously. Thus, the specimen after 15 h solution shows good comprehensive mechanical properties.

![Stress–strain curves of squeeze-cast ZL205A after solution treatment at 538 °C.](image)

The microstructure of squeeze-cast ZL205A after ageing under different time periods has typical characteristics of an Al-Cu-Mn alloy as shown in Figure 8. With the extension of ageing time, the undissolved phase gradually dissolves and black particles are dispersed in the microstructure. The transition phase θ′ is just formed when ageing starts. θ′(Al2Cu) phase and T′′′(Al12CuMn2) phase will be continuously separated and distributed on α(Al) matrix in dot form [15,16]. When the ageing time increases to 6 h, the precipitates are
fine and dispersed, as shown in Figure 8b. Because of the high microhardness of the secondary precipitated phase and the obstruction of dislocation movement, the dispersed T"(Al_{12}CuMn_2) phase can improve the strength of the alloy [14,17]. A large number of dispersed θ' phases can close the slip surface between grains and reduce the plasticity of castings [14]. When ageing time increased to 10 h, the secondary T phase grew into insoluble block, and the grain boundary is a network of cleavage matrices, which was unfavorable to the plasticity of the specimen.

The X-ray diffraction patterns of squeeze-cast ZL205A specimens after heat treatment are shown in Figure 9. The casting is mainly composed of the diffraction peaks matrix α(Al) phase and θ(Al_2Cu) and T (Al_{12}CuMn_2) phases. After 15 h of solution, the diffraction peak of the specimen is mainly in the matrix α(Al) phase, which indicates that the secondary phase is mostly dissolved in the matrix α(Al) phase. With the increase in ageing time, the diffraction peak of T(Al_{12}CuMn_2) phase increases obviously, which indicates that the volume fraction of T(Al_{12}CuMn_2) phase increases gradually, and the precipitation quantity increases. When ageing time increased to 10 h, the secondary T phase grew into insoluble black block, which was unfavorable to the plasticity of the specimen.
The mechanical properties of ZL205A squeeze castings under different ageing times are shown in Figure 10. The ultimate tensile strength of the aging specimens is obviously higher than that of the solution. It can be seen that the tensile strength of ZL205A squeeze castings increases first and then decreases with the increase of ageing time, which has three ageing stages of under-ageing, peak-ageing and over-ageing. When ageing for 6 h, the tensile strength reaches the maximum 467 MPa. Then, the tensile strength begins to decrease with the increase of ageing time, and enters the over-ageing stage. The change in the trend of yield strength is consistent with that of tensile strength. When the ageing time is 6 h, the elongation was 15.1%. When the ageing time increases to 8 h, the elongation has little change as shown in Figure 10. The microhardness of aged specimens is higher than that of solution state. The microhardness increases first and then decreases with the ageing time increases. After ageing for 6 h, the microhardness reaches maximum 156.7 HV. In comprehensive consideration, the specimen aged for 6 h show the best mechanical properties.
Figure 11 shows the tensile fracture morphology of a ZL205A alloy squeeze casting after solution treatment at 538 °C for 15 h and ageing at 155 °C. It can be seen from Figure 11 that the fracture surface is dark gray under different ageing times, mainly composed of dimples of uneven size, partial smooth shear areas and tearing edges. After 4 h ageing treatment, the dimple morphology of the ZL205A alloy tensile fracture is large and deep with a uniform distribution. There are a large number of small dimples dispersed between the large dimples, and some areas with smooth fracture structure with no tear marks, as shown in Figure 11a. After 6 h ageing, the number of dimples decreased and the area of smooth shear zone increased significantly, and the tearing edges increased; thus, the elongation decreased, as shown in Figure 11b. The microstructure of the ZL205A alloy after 6 h ageing is uniform and the number of the precipitated secondary phase is large and the distribution is dispersive, which can substantially block the dislocation movement according to the research results of the literature [18]. After ageing for 6 h, the strengthening effect of ageing is improved obviously, and the alloy shows good comprehensive mechanical properties. These results are consistent with those of the tensile tests.

Figure 11. The typical fracture morphologies of the tensile specimens of squeeze-cast ZL205A under different ageing times: (a) 155 °C × 4 h; (b) 155 °C × 6 h; (c) 155 °C × 8 h.
4. Conclusions
(1) Most of the \(\theta(\text{Al}_2\text{Cu})\) and \(T(\text{Al}_{12}\text{CuMn}_2)\) phases dissolved in the \(\alpha\text{(Al)}\) matrix after solution treatment for 15 h. When the ageing time increased to 8 h, the secondary \(T\) phase grew and the grain boundary presented a network of cleavage matrices, which was unfavorable to the plasticity of the specimen.
(2) After solution 15 h, the ultimate tensile strength reached the highest value of 381 MPa, and the elongation was 16.1\%, which were much higher than those of as-cast. The tensile strength decreased with 17 h solution.
(3) The specimen aged for 6 h showed good mechanical properties with the ultimate tensile strength of 467 MPa and the elongation of 15.1\%.

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