Study on Solidification Process of ZL114A Wheel Casting

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Abstract: In this paper, three different solidification process design schemes of the ZL114A wheel casting are discussed, in accordance with the comparative analysis of metallurgical quality statistics, a solidification order from bottom to top and from outside to inside is attained by adjusting the chiller material and reducing the pouring temperature, which meets the HB963-2005II casting standards. The average tensile strength, yield strength and elongation of the T6 state are 340MPa, 260MPa and 6.5% respectively after the T6 heat treatment and the low temperature stabilization process. The average grain size of the primary α-Al matrix is about 86μm after adding 0.11%Sb element, the morphology of the binary and ternary eutectic Si phases that distributed nearby the grain boundary are spherical and elliptical, the fracture mechanism of T6 state shows a typical dimple fracture.

1. Introduction
Aluminium alloy material has high specific strength/specific stiffness, low density, excellent corrosion resistance and processing performance. By cold/hot processing and heat treatment, it has better mechanical and chemical properties and has been widely used in aerospace, military electronics and other military equipment fields [1-5]. Compared with other forming processes of machine shaping, the Solidification process can reduce the parts assembly quantity by 55%~80%, the mass manufacturing cost by 25%~45%, and can short the manufacturing cycle by 25%~40%. And the investment in manufacturing equipment is less too [6-7]. In that way, the material and structure weight reduction of components can be realized, which has important engineering application and economic benefits. Due to its excellent casting process flow performance, al-si series casting alloys are mostly used in the manufacturing of complex structure castings by integral forming, and have high mechanical strength and plastic toughness after T6 heat treatment, and can withstand medium load [8-10].

In recent years, with the rapid development of military equipment industry, lightweight design and manufacturing has become the mainstream design direction of light armored transport vehicles. In mechanical and riveting, welding process manufacturing, the material utilization ratio is low, while the processing cost is high and manufacturing cycle is long. By using of solidification forming integrated forming manufacturing, we can realize the overall processing and manufacturing of the complex structure parts, and effectively enhance the overall stiffness of the parts [11-13]. Taking ZL114A Wheel Casting of a light armored vehicle as the research object, compared and analysed the internal metallurgy quality and the mechanical properties of ontology of the wheel casting under three different coagulation process, combined with OM, SEM and EDS, this paper completed characterization analysis of the internal microstructure of ZL114A wheel casting, and the optimization of design on solidification forming process of casting, which provide data support and reference of process design for engineering batch research on wheel casting in the field of defense equipment.
2. Preparation and Characterization

Table 1 shows the chemical composition of ZL114A alloy material. Alloy melting process: heat the high purity aluminum ingots (99.99%, mass fraction) to 730°C first and 760°C when it is completely melted. Then add in the intermediate alloy of Al-12%Si. After cooling to 660°C, add the intermediate alloy of pure Mg ingot and Al-5Ti-B to the mixture. Then heat to 770°C and overheat for 12 min before adding in the intermediate alloy of Al-5Sb for silicon phase metamorphism. Cool it to 710°C and fill in argon while adding in the hexachloroethane for refining and degassing for 15 min. After 15-minute standing time, pour in the alloy melt at 720°C.

T6 solid solution is completed by the Tianjin Hongjing HTD-720 well type solid solution furnace, (the furnace temperature control precision is ±3°C, the high temperature limit is 800°C). The aging heat treatment is completed by Hebei Rongda TNS240 digital electric drum wind drying oven (the furnace temperature control precision is ±3°C, the high temperature limit is 400°C). T6 heat treatment process uses the parameters of HB963-2013, The test intercepted ontology samples of wheel casting and processed into standard mechanical properties test samples (see figure 1). By using 400#, 1000#, 1500# sandpaper, in turn, to polish surface of the sample, the test eliminate the influence of machining grinding marks on the sample mechanics performance test results, and take the average of three test sample of mechanics performance test as the test results. The Mechanical test was conducted by WDW-100KN testing machine. The chuck movement speed is 2 mm/min. The OM testing was conducted by AX10ZIESS optical microscope. Low concentration of mixed acid was chosen as the metallographic etchant, volume ratio (HF): (HCl):(HNO₃):(H₂O)=2:3:5:195. The intergranular etchant is 1LH₂O, 57g NaCl, and 10ml H₂O₂. The characterization analysis on the fracture appearance of the tensile sample is conducted by FEI-Quanta 600 scanning electron microscope.

| chemical compositions | Si  | Mg  | Ti  | Mn  | Sb  | Cu  | Zn  | Al  |
|-----------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| mass fraction /%       | 6.85| 0.56| 0.13| 0.10| 0.11| 0.08| 0.05| Bal |

Fig. 1 The schematic of tensile specimens

3. Solidification Process Design

Figure 2 shows the structure diagram of ZL114A hub casting, Wheel hub casting as II HB963-2005 castings, structure size for Φ768 mm * 384 mm, the middle ring wall thickness size is 32 mm, flanked by uniform 8 floor, floor thickness is 12 mm, cylindrical wheel casting wall thickness size of 26 mm, for the overall loop structure. Alloy ZL114A, material state T6, bulk specimen tensile strength 310MPa, yield strength 240MPa, elongation 3.5%, casting dimensional tolerance should be in line with GB/T6414-1999 CT8. The casting material was selected as phenolic self-hardening resin sand, and the resin binder was 5235 phenolic resin, accounting for 1.2% of the total weight of molding sand. The curing time of the binder was selected as 42min ~ 50min. The molding sand is made of ordinary silica sand with particle size from 80 mesh to 160 mesh. The resin sand casting cavity is coated with zaf-3 type alcohol-based high-temperature resistant coating.

FIG. 3 shows the solidification process design schematic diagram of different ZL114A hub castings. As shown in figure 3 (a) in the coagulation process, SPR bottom diameter of 28 mm, draft Angle is
1.5°, runner type "m" layout, the structure is runner section size 58 mm x 42 mm; Wheel casting bottom cold iron material of 45 # steel, cold iron thickness of 24 mm, lateral cold iron is made of brass, 24 mm thick cold iron floor bottom cold iron material of 45 # steel, cold iron thickness of 20 mm, riser bottom section size is 142 mm x 20 mm, height of 60 mm, draft Angle is 2.5°, by m type runner layout of lead alloy melt from casting bottom, bottom-up filling deposit. In the solidification process design scheme shown in FIG. 3 (b), the cross-section size is 84mm 22mm, the cross-section height of the cross-section is 28mm from the bottom of the hub casting, the cross-section size of the inner gate is 20mm 14mm, and the number of the inner gate is 8. The cold iron at the bottom of the casting is made of brass with a thickness of 20mm. The side chillers are made of 45 # steel, the thickness of the chillers is 20mm, and the distance between the edge of the chillers and the inner gate is 40mm. The chill material of floor bottom is 45 # steel, and the thickness of the chill is 28mm. The section size of the cold iron in the middle ring is 26mm 18mm, and the distance between the two cold iron is 20mm. Casting at the top of the riser section size is 156 mm x 22 mm, height of 60 mm, draft Angle is 2.0°, through a circular runner layout of two sheets of SPR, can shorten the alloy melt casting time. 3 (c) in the solidification process design scheme of ZL114A hub casting, the bottom chill is made of brass with a thickness of 32mm, the side chill is made of brass with a thickness of 24mm, and the top chill is made of brass with a thickness of 20mm. Floor bottom cold iron material of 45 # steel, cold iron thickness is 38 mm, runner section size of 48 mm x 22 mm, SPR bottom of 26 mm in diameter, height is 88 mm, the draft Angle is 2.4°, decorate two area to the middle circle to feeding riser, riser height is 86 mm, the draft Angle is 3.0°, through the runner at both ends of connected directly with the wheels of ZL114A castings, alloy melt filling. The three casting systems described in figure 3 are all open casting systems.

Fig.2 The three-dimensional structure diagram of ZL114A wheel casting.
(a) top view; (b) sectional view

Fig.3 The solidification process schematic of ZL114A wheel casting.
(a) process 1; (b) process 2; (c) process 3.
4. Statistical Analysis of Metallurgical Defects

Table 3 shows the statistical results of internal metallurgical defects of ZL114A hub casting under different solidification process design schemes. According to the test results in table 3, there are two pinholes and two porosity in the hub casting of ZL114A under solidification process plan 1. The pinhole defects are shown in figure 4 (e). The porosity defects are mainly located at the top of the hub casting. Coagulation process under 1 wheel casting wall under the brass cold iron chill, alloy melt from inside extraversion directional solidification, and on the top of the riser feeding the alloy melt can be realized on the end of solidification feeding, but considering the high heat conduction ability, brass cold iron wall in some parts of solidification before has not been effective riser feeding, feeding channel has been rapid cooling solidification, and lose the function of feeding, leading to the loose defects in local area [14-15]. There are 2 pinholes, 2 slag inclusion, 4 porosity and 1 porosity in the inner part of the lower hub casting in solidification process plan 2. The porosity defects are shown in figure 4 (d). According to the analysis, the flow of the ring runner under process plan 2 is relatively long. When the alloy melt is filled in the inner gate farthest from the runner, the coating, which is falling off due to repeated scour of the mold wall, will generate oxide inclusion slag in high temperature, leading to casting defects. In addition, the distance between the two straight runner in the ring runner is far, so the gas involved in the early filling period is too late to escape and discharge, so it is wrapped in the alloy melt and filled into the mold cavity, resulting in porosity defects in the casting. Under solidification process plan 3, there are 2 pinholes, 5 slag inclusion, 6 porosity, 2 cold insulation and 3 porosity in the inner part of ZL114A hub casting. The slag inclusion defects are shown in figure 4 (a), the cold insulation defects are shown in figure 4 (b), and the involved porosity defects are shown in figure 4 (c). Analysis shows that the original intention of solidification process plan 3 is to improve the process yield of ZL114A hub casting as much as possible, and on the basis of a large number of external coolers, the sequential solidification of ZL114A hub casting from bottom to top and from outside to inside can be realized quickly. The production rate of the casting in process plan 3 is 92%, and the rapid filling of the alloy melt is realized through the design of the runner. At the initial filling stage of alloy melt, a large range of scour occurred in the interior of the runner and the surface coating of the runner, and a large amount of slag was involved. Wheel casting side arm, lower cold iron on the lateral and rapid chilling effect in the early solidification provides extremely high cooling speed, feeding channel, resulting in a large number of chill blocks, lost at the end of solidification feeding effect, and some chilling surface is realized in the early solidification solidification shell, the filling process in the sequence of alloy melt, the attachment in solidification cooling solidification shell surface again, cold insulation defects. Due to the simple design of the runner and the runner, a large amount of gas is rolled into the mold cavity of the hub casting at the initial filling stage, resulting in serious porosity defects.

According to the statistical results of metallurgical defects in table 2 and figure 4, the solidification process was optimized on the basis of solidification process plan 1. According to the analysis, the loose defect in process plan 1 is caused by the supplementary shrinkage channel at the early solidification stage being blocked by chilling. Therefore, the side cooling iron material of ZL114A hub casting in process plan 1 was replaced with brass material and 45 # steel. At the same time, there are pinhole defects in process plans 1, 2 and 3. According to relevant data, hydrogen saturation in molten metal is much higher than that in solidified metal block, and pinhole defects in aluminum alloy can be improved by adjusting casting temperature [16]. Based on coagulation process plan 1 will alloy melt pouring temperature changed from 720°C to 705°C. After the above process improvement, no obvious pinhole, slag inclusion, porosity, cold isolation and porosity defects were observed in the inner casting of ZL114A wheel hub castings casted by solidification process plan 1. The quality of internal metallurgy met the technical requirements.
### Table 2 The T6 heat treatment parameters of ZL114A stent casting defects plan

| defects      | pinhole | slag | shrinkage | cold lap | stoma; |
|--------------|---------|------|-----------|----------|--------|
| 1            | 2       | 0    | 2         | 0        | 0      |
| 2            | 2       | 2    | 4         | 0        | 1      |
| 3            | 2       | 5    | 6         | 2        | 3      |

#### Fig.4 The metallurgical defects of the ZL114A wheel casting:
(a) slag; (b) cold lap; (c) involvement stoma; (d) shrinkage; (e) pinhole

### 5. Mechanical Property Test

After T6 heat treatment, ZL114A hub castings were stabilized for 1 hour at 60°C below zero (liquid nitrogen). After that, six samples were cut from the side of the hub castings for mechanical properties test and their average values were taken as the test results of ZL114A hub castings, as shown in Fig.5. As can be seen from Fig.5, the average tensile strength, yield strength and elongation of ZL114A hub casting in T6 heat treatment are 340MPa, 260MPa and 6.5% respectively, which meet the technical index requirements of the product.

#### Fig.5 The test results of mechanical properties: (a)tensile strength; (b)yield strength; (c) elongation
6. Microstructure Analysis

Fig. 6 shows the microstructure test results of ZL114A hub casting sample. After Sb element metamorphism, the eutectic silicon phase morphology of ZL114A alloy in as-cast microstructure was more uniform, and the morphology was mostly spherical or elliptical. The average grain size of primary α-Al was about 86 μm, as shown in Fig. 6(a). Fig. 6(b) shows the back scattering SEM test results of the microstructure of ZL114A hub casting after T6 heat treatment, in which the Si phase particles in binary and ternary eutectic phases distributed along the grain boundary are more evenly dispersed, as shown in Fig. 6(b). Fig. 6(c) shows the T6 fracture SEM morphology of wheel casting. Its fracture mechanism is typical fracture toughness nest, and after the T6 heat treatment, the morphology of the eutectic Si phase distributed along the grain boundary in the as-cast microstructure was mostly spherical. Under the loading stress of the test, the microcracks start from the hard and brittle silicon phase region, and under the loading stress of the test, they are continuously superimposed and extended along the grain boundary. Finally, a large number of microscopic dimples are left on the fracture surface, and the dimples are elliptical or spherical in shape. Fig. 6(d) shows the results of SEM scanning and EDS analysis on the surface of T6 state fracture. The phase analysis of the bright area is mainly composed of Al, Mg and Sb elements, among which Sb elements account for 71.51% and are the main elements. Analysis suggests that during the solidification nucleation and crystallization growth process of Si phase, Sb atoms are continuously filled to the growth interface front of Si phase, which inhibits the one-dimensional growth of Si phase, continuously changes the growth morphology of Si phase, and has a metamorphic effect [17], improving the distribution and morphology of Si phase in ZL114A alloy material and improving the mechanical properties of the alloy material.

Fig. 6 The test results of mechanical properties.
(a) as-cast organization; (b) SEM of the T6 state; (c) fracture SEM of the T6 state; (d) fracture EDS of the T6 state

7. Conclusion
(1) We chose open casting system, and contrastively analysed the three different kinds of coagulation process design scheme, by adjusting the cold iron material and reduce the pouring temperature. When using solidification process design scheme 1, the sequential solidification of ZL114A hub casting from bottom to top and from outside to inside was realized by adjusting the cold iron material and reducing the pouring temperature, which avoid the pinhole and the loose defects, meet the requirement of II HB963-2005 casting technology.
(2) After T6 heat treatment and low temperature (60°C below zero) stabilization treatment, the T6 average tensile strength, yield strength and elongation of ZL114A hub casting are 340MPa, 260MPa and 6.5%, respectively.

(3) 0.11% weight % of Sb element was added, and Sb atoms were continuously filled to the growth interface frontier of the silicon phase, which inhibited the one-dimensional growth of the Si phase. The distribution of binary and ternary eutectic Si phases along the grain boundary appeared spherical or oval. The average grain size of primary α-Al matrix was about 86μm. The fracture mechanism of T6 is a typical dimple fracture. The microcracks start from the hard and brittle Si phase particles at the grain boundary and then extend along the grain boundary, leaving a large number of microscopic dimples on the fracture surface.

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