IOP Conf. Series: Materials Science and Engineering **230** (2017) 012036 doi:10.1088/1757-899X/230/1/012036

# Fabrication and Properties of Al-Cu-Mg-Zn Series Alloys with Low Hot Cracking Tendency for Liquid Forging

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**Abstract.** Twelve new kinds of Al-Cu-Mg-Zn alloys with different components were designed on the basis of optimizing main alloying elements, including Zn, Mg and Cu to resolve hot crack problems of Al-Cu-Mg-Zn series alloys during liquid forging. Hot cracking susceptibility (HCS) was adopted to characterize hot cracking tendency, evaluated using constrained rod casting in a steel mould. The influence of those three main alloying elements on the hot cracking tendency and the mechanical properties of new alloys were researched. The results show that most of those new alloys have better hot crack tendency performances than 2024 alloy and 7075 alloy. The 8th alloy, Al-5Cu-4.5Mg-2.5Zn, shows best mechanical properties after liquid forging, which hot crack tendency index is the lowest, only reaching 40. The tensile strength is 327 MPa and the elongation to fracture is 2.7%, which Brinell hardness reaches 107 $N/mm^2$.

## 1. Introduction

As the lightweight requirements in the field of aerospace, weaponry and transportation enhanced increasingly, it is expected more and more intensively to use aluminum instead of steel, especially in those important mechanical parts and structural components with high demand of lightweight that equipped in spacecraft, tanks, artillery, aircraft, high-speed rails and cars [1-2]. In recent years, the trend to use aluminum and aluminum alloys to replace original steel structures is growing dramatically. For example, aircraft components, automobile hubs, bumpers, tank road wheels, helicopter rotating rings and stationary rings, train cylinders and pistons are manufactured by forging used aluminum alloy. However, traditional die forging technology cannot completely meet the requirements to manufacture and use those aluminum alloy parts. And the fact gives more and more attentions on the research of liquid forging and semisolid forging forming technology [3].

Liquid forging forming technology is a process that a certain amount of molten metal liquid is poured directly into metal mold, fills the mold, solidifies and crystallizes with some plastic deformation under special pressure, to obtain net-shape parts which structure are closely knitted. Its advantages are saving time and energy, efficient utilization. What’s more, the parts with the final size show good performances close to hot forging parts. But as a result of liquid forging forming mainly companied with solidification, it is hard to avoid the production of hot cracks caused by the uneven stress field during the end of solidification, which seriously restrict the development of liquid forging forming technology[1,4].

Combined the advantages and disadvantages of Al-Cu series alloys and Al-Zn series alloys, it was researched and discussed how to resolve the production of hot cracks during the aluminum alloy liquid forging forming process, from the perspective of alloy element ratios, to fabricate aluminum alloys with less hot cracks and better comprehensive performances for liquid forging forming technology. Hot cracking tendency and mechanical properties of new designed aluminum alloy were studied.

## 2. Experimental procedure

### *2.1. Component design of aluminum alloy and alloy melting*

Commercial extruded 2024 aluminum alloy rods of 30 mm diameter were used as matrix materials. According to the single variable method, some new aluminum alloys with low hot cracking tendency were designed and fabricated by adding industrial pure zinc and magnesium, and Al-Cu (50%) intermediate alloy. Hot cracking susceptibility of new aluminum alloys, 2024 aluminum alloy and 7075 aluminum alloy were compared. The chemical components of 2024 and 7075 aluminum alloys were shown in table 1.

**Table 1.** Chemical components of 2024 and 7075 aluminum alloys

| Elements (*wt*. %) | Cu | Mg | Zn | Cr | Mn | Ti | Fe | Si | Al |
|---|---|---|---|---|---|---|---|---|---|
| 2024 | 4.90 | 1.13 | 0.10 | 0.01 | 0.82 | 0.04 | 0.20 | 0.20 | others |
| 7075 | 1.54 | 1.29 | 6.18 | 0.17 | 0.28 | - | 0.35 | 0.25 | others |

Combined with Al-Zn-Mg-Cu series alloys phase diagram [5], it must ensure that content of zinc element is lower than 6%, that content of Mg element is higher than 2%, and that content of Cu element is higher than 1.5%, to reduce the alloy hot cracking tendency and satisfy the aluminum alloy usage requirement of the strength, hardness and toughness. Main content of alloy elements were optimized by the theoretical limit. And $1^{\#}$ ~ $12^{\#}$ new aluminum alloys were designed by only changing one of three main alloying elements component proportions, as shown in table 2.

**Table 2.** Component proportions of twelve kinds of aluminum alloys

| Number | Mass fractions /Wt. % | | |
|---|---|---|---|
| | Zn | Mg | Cu |
| $1^{\#}$ | 1.1-2.0 | 3.0-3.9 | 4.5-5.4 |
| $2^{\#}$ | 2.1-3.0 | | |
| $3^{\#}$ | 3.1-4.0 | | |
| $4^{\#}$ | 4.1-5.0 | | |
| $5^{\#}$ | 5.1-6.0 | | |
| $6^{\#}$ | 2.1-3.0 | 1.0-1.9 | 4.5-5.4 |
| $7^{\#}$ | | 2.0-2.9 | |
| $8^{\#}$ | | 4.0-4.9 | |
| $9^{\#}$ | 2.1-3.0 | 3.0-3.9 | 1.5-2.4 |
| $10^{\#}$ | | | 2.5-3.4 |
| $11^{\#}$ | | | 3.5-4.4 |
| $12^{\#}$ | | | 5.5-6.4 |

The amount of alloys were calculated and weighed according to the design as shown in table 2. Melting furnace was heated to 300 ℃ ~ 400 ℃, and certain amounts of 2024 aluminum alloy and Al-

Cu (50%) intermediate alloy were added and heated up to 750 ℃, waiting to melt. And a small amount of NaCl & KCl covering agent was sprinkled. Then furnace temperature was cooled to 700 ℃, pure magnesium and pure zinc was added respectively and melted. When the furnace temperature was back to 710 ℃ ~ 730 ℃, melted alloy was refined twice adding refining and degassing agent, $C_2Cl_6$.

### *2.2. Hot cracking tendency test*

Considering the causes of hot cracks, hot cracking susceptibility was adopted to characterize hot cracking tendency, evaluated using constrained rod casting in a steel mold [6-7], which was compared with 2024 and 7075 aluminum alloy performances, to design a new type of aluminum alloys with the lowest hot cracking tendency. Figure 1 and figure 2 show the schematic and physical pictures of hot cracking rod mold respectively. The mold was preheated to 300 ℃ before the melted alloy was poured in when the temperature of melt reached 730 ℃. The melt filled the cavity and solidified. During this process, melted alloy solidification and contraction were limited by the mold cavity, to make the alloy constriction impeded and produce hot cracks. The hot cracking tendency of different aluminum alloys were compared from the position and the crack depth. Cracking rods were constrained from two parts, the runners and the balls, in the process of solidification. By observing hot cracking rod samples and recording, hot cracking susceptibility indexes (HCS) were calculated by the Formula 1 as shown.

$$\mathrm{HCS} = \sum\left(\omega_{\mathrm{crack}} \cdot f_{\mathrm{length}} \cdot f_{\mathrm{location}}\right) \tag{1}$$

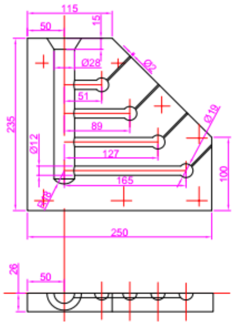


**Figure 1.** The schematic picture of hot cracking rod mold (mm)

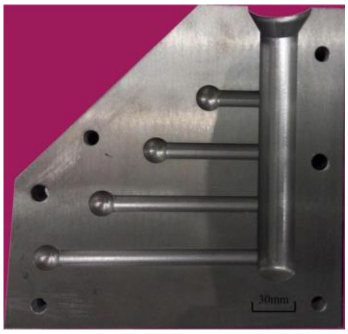

**Figure 2.** The physical picture hot cracking rod mold

### *2.3. Liquid forging forming process*

Liquid forging forming mold was assembled and preheated to 300 ℃, which surface was coating with graphite as mold release agent. The melted alloy heated to 730 ℃ was poured into cylindrical mold, loaded quickly by forging hydraulic machine and maintained a while. The loading pressure was 30 MPa, and the holding time was 30 seconds. Cylinder forming parts which were 65 mm in diameter and 60 mm in height were prepared after solidification. The microstructures and properties were researched after those forming parts sampled.

## 3. Results and discussion

### *3.1. Analysis of hot cracking tendency test*

In hot cracking tendency test, all designed aluminum alloys formed completely, and the situation of insufficient pouring or no-fully filling did not appear.

figure 3 shows hot cracking constrained rod hairline and fracture positions on parts of the new aluminum alloys, including 2024 and 7075 aluminum alloys. It can be seen that most of aluminum rod fractures and hairlines exist on the root of the main runner. The fractures concentrate on the longest bars, and the hairlines and partial fractures concentrate on the second and third longest bars. However $10^{\#}$ and $12^{\#}$ aluminum alloys are different, that fractures exist on the end of rod near to the ball. 2024 and 7075 aluminum alloy show the same result as most of new aluminum alloy.

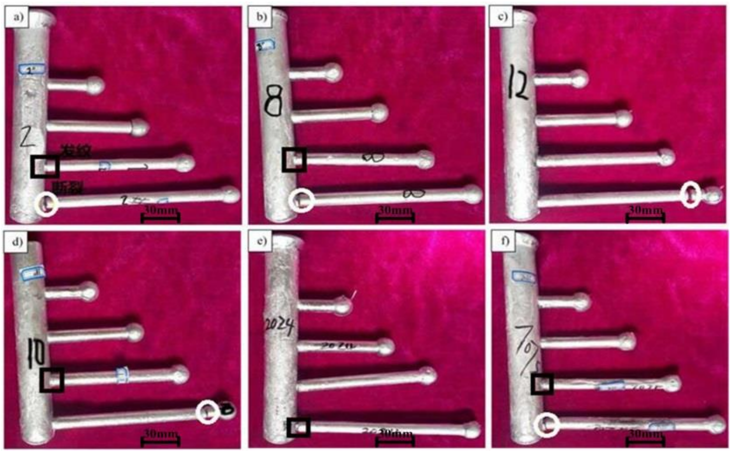

**Figure 3.** Crack position schematic pictures of parts of hot cracking tendency testing samples
a)2#; b)8#; c)12#; d)10#; e) 2024 alloy; f) 7075 alloy
2# is Al-5Cu-3.5Mg-2.5Zn alloy; 8#is Al-5Cu-4.5Mg-2.5Zn alloy;
12# is Al-6Cu-3.5Mg-2.5Zn alloy; 10# is Al-3Cu-3.5Mg-2.5Zn alloy

According to the principle of hot cracking tendency test and the situation of alloy hot cracking rod cracks, hot cracking susceptibility indexes are calculated, using hot cracking susceptibility formula. The results of hot cracking tendency test are obtained, as shown in table 3.

**Table 3.** Results of hot cracking tendency test

| Number | HCS | Number | HCS |
|---|---|---|---|
| 7075 | 72 | 6# | 56 |
| 2024 | 68 | 7# | 48 |
| 1# | 40 | 8# | 40 |
| 2# | 40 | 9# | 96 |
| 3# | 56 | 10# | 88 |
| 4# | 56 | 11# | 44 |
| 5# | 64 | 12# | 56 |

Figure 4 shows the influence of zinc, magnesium, and copper alloying element percentages on hot cracking tendency of aluminum alloy. It can be found that hot cracking tendency of the designed aluminum alloys are lower than 7075 aluminum alloy and 2024 aluminum alloy which are used more in liquid forging forming technology. Also, it can be seen that the hot cracking tendency of some alloys which contain less copper element percentages performance higher than 2024 and 7075 aluminum alloys.

As it is introduced above, there are limit percentages of the three alloying elements. From figure 4, with the decrease of zinc element percentages during the limit, hot cracking tendency are also gradually reduced. When zinc element percentage is less than 3%, hot cracking tendency keeps constant basically. And when magnesium element percentage is 3% ~ 5%, the hot cracking tendency is also consistent. But when the percentage of magnesium element is less than 3%, the hot cracking tendency becomes increase instead of decreasing when reduce magnesium content. Copper element is the main influence factor, and the influence rule is different. When the percentage of copper element is more than 4%, the cracking tendency reduced following the decrease of copper element. But when copper content is lower than 4%, the hot cracking tendency of aluminum alloy increases sharply as the same change, even being higher than the HCS of 7075 aluminum alloy. The HCS of aluminum alloys are up to 88 and 96.

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The hot cracking tendency test shows that the content of Cu element has a big effect on hot cracking tendency of aluminum alloy, and that hot cracking tendency increases sharply when the percentage of copper element keeps in a low level. The reason is that a large number of *S* ($Al_2CuMg$) phase eutectic organizations are generated when the concentration of copper element is lower. *S* ($Al_2CuMg$) phases are bulky and have a strong fracturing effect on aluminum alloy, and numbers of crack sources are produced, to make the hot cracking tendency high.

The lowest hot cracking susceptibility index is 40 among all of the new designed aluminum alloys and three kinds of aluminum alloys reach this index. They are 1# (Al-5Cu-3.5Mg-1.5Zn) aluminum alloy, $2^{\#}$ (Al-5Cu-3.5Mg-2.5Zn) aluminum alloy and $8^{\#}$ (Al-5Cu-4.5Mg-2.5Zn) aluminum alloy, respectively. And the hot cracking susceptibility index of $11^{\#}$ (Al-4Cu-3.5Mg-2.5Zn) aluminum alloy is also relatively lower, only 44.

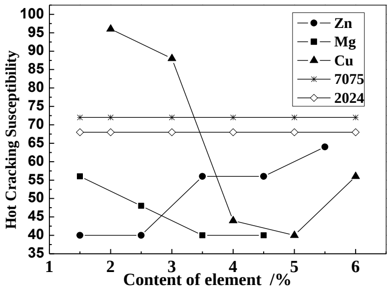


**Figure 4.** Influence of zinc, magnesium, and copper alloying element on hot cracking tendency of aluminum alloy

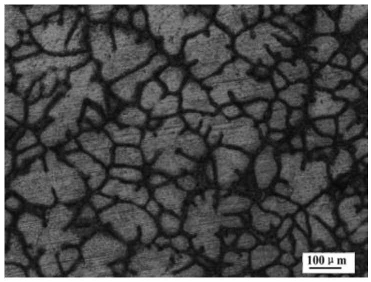


**Figure 5.** Microstructure of aluminum alloy formed by liquid forging

*3.2. Analysis of organizations and mechanical properties*

Figure 5 is the microstructure of new aluminum alloy parts formed by liquid forging. The organization of new aluminum formed by liquid forging is a mixed organization consisting of free dendrites and equiaxed grains produced from dendrites deformation and breakage, just like typical casting organization. What's more, there are numerous net-like and thick non-equilibrium eutectic structures distributed between grain boundaries. And most of dendrites present on trend to become equiaxed grains. There was a large different temperature distribution on alloy melt during the liquid forging process. Alloy melt on lower temperature rapidly nucleated and grew, forming fine equiaxed grains because of numerous nucleation sites. Because internal heat of the melt was not easy to loss, temperature was higher and nucleation particles were less. The release of the crystallize latent heat caused crystal nucleus to grow up rapidly and form dendrites. On the effect of outside loads, dendrites were deformed and broken into rose-shape organizations. At the same time, the solidification speed under outside load of alloy melt was too fast, and high percentages of alloy elements distributed unevenly. So the organization deviated from the equilibrium state in different levels, and numbers of non-equilibrium eutectic organizations formed and segregated in the grain boundary.

It is known that there is a big difference on solubility of three elements in aluminum, Zn, Mg and Cu [8-9]. So with the difference of Zn, Mg and Cu percentages, all the designed aluminum alloys contain different intermediate phases and eutectic organizations, showing different mechanical properties.

The four new designed aluminum alloys were sampled, including $1^{\#}$ (Al-5Cu-3.5Mg-1.5Zn) alloy, $2^{\#}$ (Al-5Cu-3.5Mg-2.5Zn) alloy, $8^{\#}$ (Al-5Cu-4.5Mg-2.5Zn) alloy and $11^{\#}$ (Al-4Cu-3.5Mg-2.5Zn) alloy. Tensile strength, hardness and elongation tests have completed, and the results are shown as figure 6.

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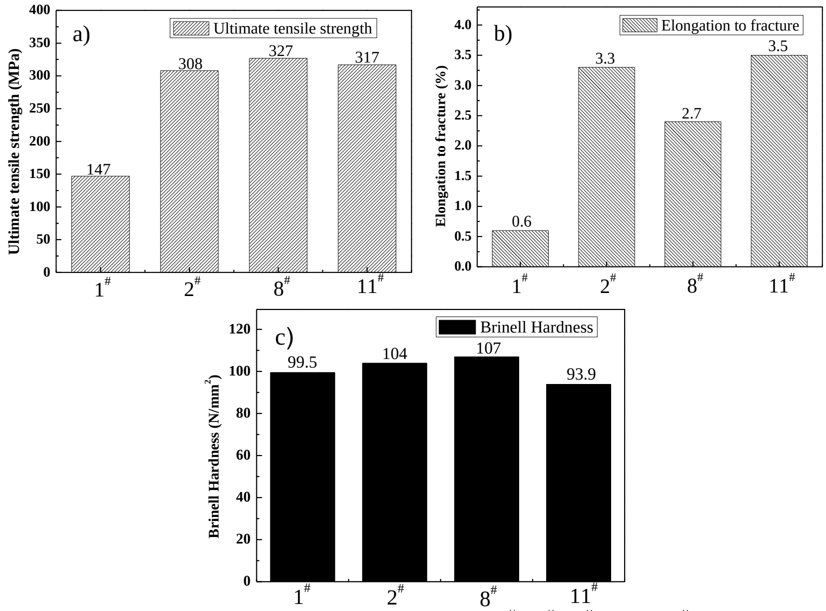


**Figure 6.** Mechanical properties test results of 1#, 2#, 8# and 11# aluminum alloys
a) Tensile strength; b) Elongation; c) Hardness
1# is Al-5Cu-3.5Mg-1.5Zn alloy; 2#is Al-5Cu-3.5Mg-2.5Zn alloy;
8# is Al-5Cu-4.5Mg-2.5Zn alloy; 11# is Al-4Cu-3.5Mg-2.5Zn alloy

It can be found that mechanical properties of 1# (Al-5Cu-3.5Mg-1.5Zn) aluminum alloy are obviously lower. After analyzing the microstructure and tensile fracture surface morphology (as figure 7), it is concluded that a large amount of shrinkage defects and inclusions existing lead to worse mechanical performances of 1# aluminum alloy.

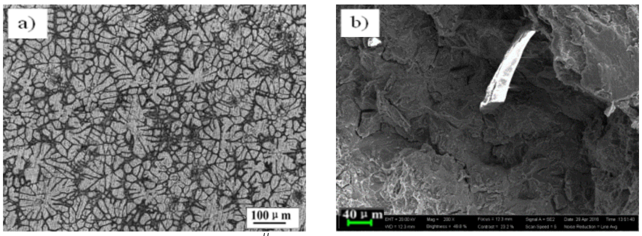


**Figure 7.** Microstructures of 1# (Al-5Cu-3.5Mg-1.5Zn) aluminum alloy
a) Metallographic structure; b) shrinkage defects and inclusions

From figure 6, 2#, 8# and 11# aluminum alloys except 1# aluminum alloy show excellent mechanical properties: tensile strength is about 310 MPa, Brinell hardness is about 100 N/mm$^2$ and elongation to fracture reach to 3% at the same time.

Compared with 2# alloy, it is found that the strength and hardness of 8# alloy is higher, but the elongation is lower. The reasons are analyzing and discussing, combined with microstructures (as figure 8a, 8b, 8c, 8d) and XRD results (as figure 9). Compared with 2# alloy, the percentage of Mg element in 8# alloy is on the high side. The increasing content of $\eta$ ($MgZn_2$) phases in 8# alloy enhances dispersion-strengthening effect and leads to ascension of strength and hardness of 8# alloy. At the same time, the number of net-like eutectic organization among grain boundaries is bigger, causing the lower alloy elongation [10-11].

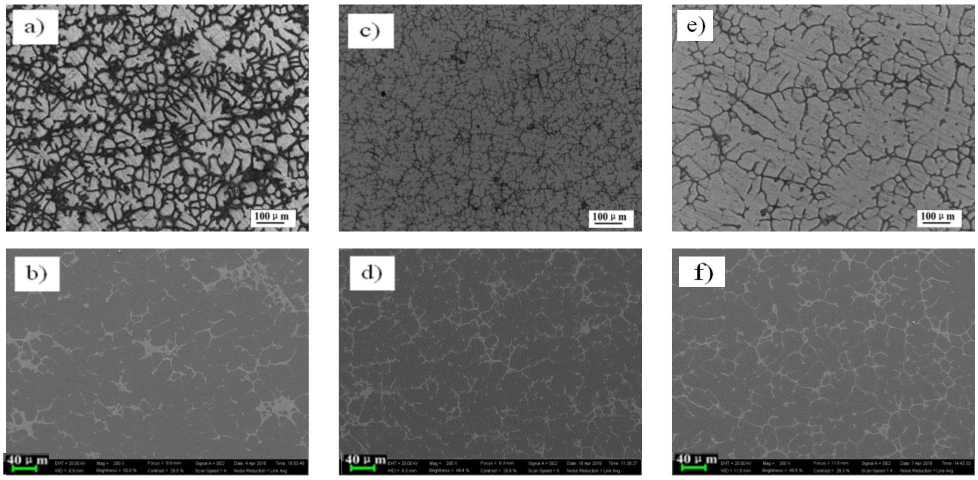


**Figure 8.** Metallographic image and Scanning Electronic Microscope image of 2#, 8# and 11# aluminum alloys
a), b) 2# alloy; c), d) 8# alloy; e), f) 11# alloy
2#is Al-5Cu-3.5Mg-2.5Zn alloy; 8# is Al-5Cu-4.5Mg-2.5Zn alloy;
11# is Al-4Cu-3.5Mg-2.5Zn alloy

Compared 11# and 2# alloy, 11# alloy shows higher strength and elongation, but its hardness is relatively lower. In terms of components, the content of Cu element in the 11# alloy is lower. The content of $\theta$ ($Al_2Cu$) phases reduces or even disappears (as figure 9), but the $S$ ($Al_2CuMg$) phases formed by Al, Mg and Cu elements disperses in 11# alloy (as figure 8e, 8f), resulting the higher strength. And in 2# alloy, solution strengthening effect caused by $S$ ($Al_2CuMg$) phases and $\theta$ ($Al_2Cu$) phases, leads higher hardness in 2# alloy (as figure 9). And also, the presence of net-like eutectic organization must make the toughness and plasticity be weakened, and elongation is lower.

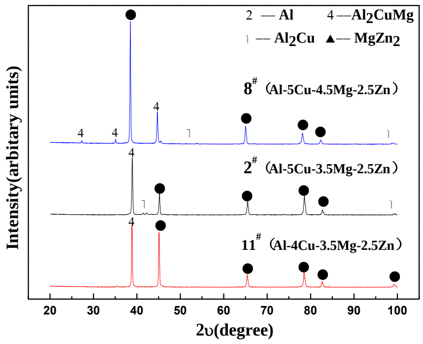


**Figure 9.** X-Ray Diffraction results of 2#, 8# and 11# aluminum alloys
2#is Al-5Cu-3.5Mg-2.5Zn alloy; 8# is Al-5Cu-4.5Mg-2.5Zn alloy;
11# is Al-4Cu-3.5Mg-2.5Zn alloy

## 4. Conclusions

The different contents of Zn, Mg and Cu elements determine the differences of microstructures and mechanical properties in aluminum alloys. New high-strength aluminum alloy using in liquid forging with low hot cracking tendency and great comprehensive performances was fabricated by designing different percentages of alloying elements.

(1) The hot tearing susceptibility indexes of 7075 aluminum alloy and 2024 aluminum alloy are 72 and 68 respectively, evaluated using constrained rod casting in a steel mold. The hot cracking tendency of most of new designed high-strength aluminum alloy is lower than them.

(2) Contents of Zn, Mg and Cu elements affect the hot cracking tendency. During a certain range, the hot cracking tendency indexes decrease as the content of zinc element reducing and the content of Magnesium element increasing. When the percentage of copper element is more than 4%, the cracking

tendency reduced following the decrease of copper element. But when copper content is lower than 4%, the hot cracking tendency of aluminum alloy increases sharply following the decrease of copper.
(3) Among all of new designed aluminum alloy, the smallest hot tearing susceptibility index is 40, and three designed alloys reach this level. They are $1^{\#}$ (Al-5Cu-3.5Mg-1.5Zn) alloy, $2^{\#}$ (Al-5Cu-3.5Mg-2.5Zn) alloy, $8^{\#}$ (Al-5Cu-4.5Mg-2.5Zn) alloy, respectively.
(4) The microstructure of new types of Al-Cu-Mg-Zn alloys after liquid forging forming are similar, which consist of dendrites, equiaxed grains and net-like eutectic organizations and intermediate phases dispersed-distributing among grain boundaries.
Considering the influence of main element percentages on hot cracking tendency, microstructures and mechanical properties, $8^{\#}$ (Al-5Cu-4.5Mg-2.5Zn) aluminum alloy shows the optimal performances among the twelve kinds of designed aluminum alloys. Its hot tearing susceptibility (HCS) index is 40, and tensile strength is 327 MPa. And the elongation to fracture is 2.7%, which Brinell hardness reaches 107 $N/mm^2$.

**Acknowledgements**
The authors express their appreciation for the financial support of International Cooperation Project of the Ministry of Science and Technology of China under Grant No. 2014***50320.

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