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Effect of alloying on high temperature fatigue performance of ZL114A (Al−7Si) alloy

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Abstract: The effect of Cu, Fe and Ni on high-temperature mechanical performance and fatigue properties of ZL114A alloy was studied through high temperature fatigue test and SEM. The results show that the three elements have a detrimental influence on high temperature cyclic fatigue life. When the contents (mass fraction) of Fe, Cu and Ni in ZL114A alloy are 0.28%，1.53% and 0.16%, respectively, the high temperature tensile strength and cyclic fatigue of ZL114A alloy are improved from 194 MPa and 40.2 MPa to 236 MPa and 48.2 MPa by alloying. The main reason that high temperature tensile strength and cyclic fatigue of ZL114A alloy are improved significantly is that the three elements greatly improve the proportion of Cu/Mg in ZL114A alloy and nickel content.

Key words: aluminum alloys; alloying; high temperature fatigue; fracture

1 Introduction

Automobile industry is one of the pillar industries for national economy in many countries [1,2]. With the development of technology and increasing requirements of energy-saving and environmental protection, study on high efficiency and low consumption automobile has become an important issue in automobile industry development in the new era, which results in the auto parts tend to be lightweight, toughened and composite [3−5]. Many structural parts often need to withstand high-temperature alternating loads during working. Under condition of high-temperature alternating loads, a part is prone to have fatigue fracture, which seriously affects the life and reliability of the part [6−10]. Therefore, the study on enhancing the high-temperature fatigue toughness of metallic materials has important values for both theoretical study and practical application. Alloying is the primary mean for getting high performance in cast aluminum alloys and also the development direction for Al alloy in the future [11−13]. Previous researches show that Mg and Cu play an important role in solid solution strengthening and can effectively improve the mechanical properties of Al alloy [13]. In addition, Ni, Mn, Zn and other elements also have certain influences on mechanical properties of the Al alloy [14−16].

At present, the researches on aluminum alloy fatigue are rather developed and most of them focused on high-temperature low-cycle fatigue. There are few reports on high-temperature high-cycle fatigue and the mechanism of high-temperature fatigue [17]. Most choices of alloying elements are concentrated in Mg, Zn and Mn elements. While the research on Fe, Cu and Ni elements, especially their joint effect, is very few. In this work, ZL114A, the main material of domestic engine cylinder head, is selected. The adding elements for ZL114A are determined as Cu, Fe and Ni. An orthogonal test involving three factors and three levels is conducted to study the high-temperature fatigue toughness and fracture mechanisms in aluminum alloys of ZL114A with different compositions at the same service temperature (200 °C). And through discussing the influence of different defects such as fatigue crack formation, crack growth, as well as short-break, a theoretical basis is provided for scientific research and practical production.

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2 Experimental

ZL114A alloy was employed as the raw material. Cu, Ni and Fe were added in ZL114A to form Al−50%Cu (mass fraction, similarly hereinafter), Al−10%Ni and Al−20%Fe master alloys; also 0.03%Sr was added, its contents were 0.1%, 0.2% and 0.3% respectively. As a result, Fe contents were 0.1%, 0.14% and 0.28% respectively, Cu contents were 0.5%, 1% and 1.5% respectively; Ni contents were 0.1%, 0.15% and 0.2% respectively, perchloroethane (dosage is 1% of alloy) was used for refining. The chemical composition of ZL114A alloy was given in Table 1. After alloy smelting, the test bars were cast and processed into specimens according to GB 3075—82 requirements. The best heating treatment conditions were determined through the orthogonal test. The solution temperature was kept at 535 °C for 8 h and ageing temperature was kept at 165 °C for 6 h. To shorten the test period, the load intensity at 106 cycles was selected as fatigue limit, the ratio of symmetric tensile-compressive stress is −1, test frequency was 10 Hz, test waveform was sine wave, and the specimen was heated by a built-in furnace of the testing machine with a control accuracy of ± 1 °C. The specimens were analyzed through XL30 ESEM-TMP.

Table 1 Chemical composition of ZL114A alloy (mass fraction, %)

Si	Mg	Fe	Ti	Mn	Al
7.2	0.54	0.11	0.12	<0.1	Bal.

3 Results

3.1 Orthogonal test

After the orthogonal test, the specific compositions obtained by spectral analysis and design values of alloys for each group are shown in Table 2, where No. 0 specimen is ZL114A+0.03%Sr. From Table 2, the results of the ZL114A alloy strengthening test is satisfying.

3.2 High-temperature mechanical performance of specimens

After solid solution treatment at 535 °C for 8 h and aging treatment at 165 °C for 6 h, the static tensile performance of specimen in each group was tested with the HT−9710-100 high-temperature fatigue testing machine. The temperature was selected as 200 °C (470 K), and experimental results are shown in Table 3.

3.3 High-temperature fatigue toughness of specimens

The measured fatigue cycle data of specimens in each group are compared with those of No. 0 specimen. The stress—cycle number curves are shown in Fig. 1.

From the above stress — cycle number curves calculated based on ladder method, it is clear that there are three groups get high temperature fatigue toughness, namely specimens 3, 6 and 9 after alloying of ZL114A. Moreover, specimen 9 not only has the largest incensement in high temperature fatigue toughness, but also derives the best high temperature mechanical properties based on ladder method. The stress—cycle number curves of specimens 0 and 9 (fatigue life curve) are shown in Fig. 2.

Table 2 Results of orthogonal test

No.	*w*(Si)/%	*w*(Mg)/%	*w*(Fe)/%		*w*(Cu)/%		*w*(Ni)/%		*w*(Al)/%	*w*(Sr)/%
			Expect	Reality	Expect	Reality	Expect	Reality		
1	7.03	0.47	0.1	0.10	0.5	0.47	0.1	0.10	91.69	0.03
2	6.90	0.49	0.1	0.10	1.0	0.98	0.15	0.15	91.25	0.03
3	6.87	0.47	0.1	0.10	1.5	1.48	0.2	0.19	90.76	0.03
4	6.85	0.43	0.2	0.13	0.5	0.46	0.15	0.14	91.87	0.02
5	6.94	0.45	0.2	0.14	1.0	1.00	0.2	0.19	91.18	0.02
6	6.81	0.42	0.2	0.14	1.5	1.53	0.1	0.10	90.91	0.02
7	6.91	0.39	0.3	0.27	0.5	0.48	0.2	0.19	91.71	0.02
8	6.96	0.39	0.3	0.28	1.0	0.97	0.1	0.10	91.26	0.02
9	6.95	0.39	0.3	0.28	1.5	1.53	0.2	0.16	90.64	0.02
0	7.20	0.54		0.11		0		0	91.93	0.03

Table 3 High-temperature tensile strength of specimens

Alloy No.	0	1	2	3	4	5	6	7	8	9
Tensile strength/MPa	194	162	178	206	176	190	220	188	176	236

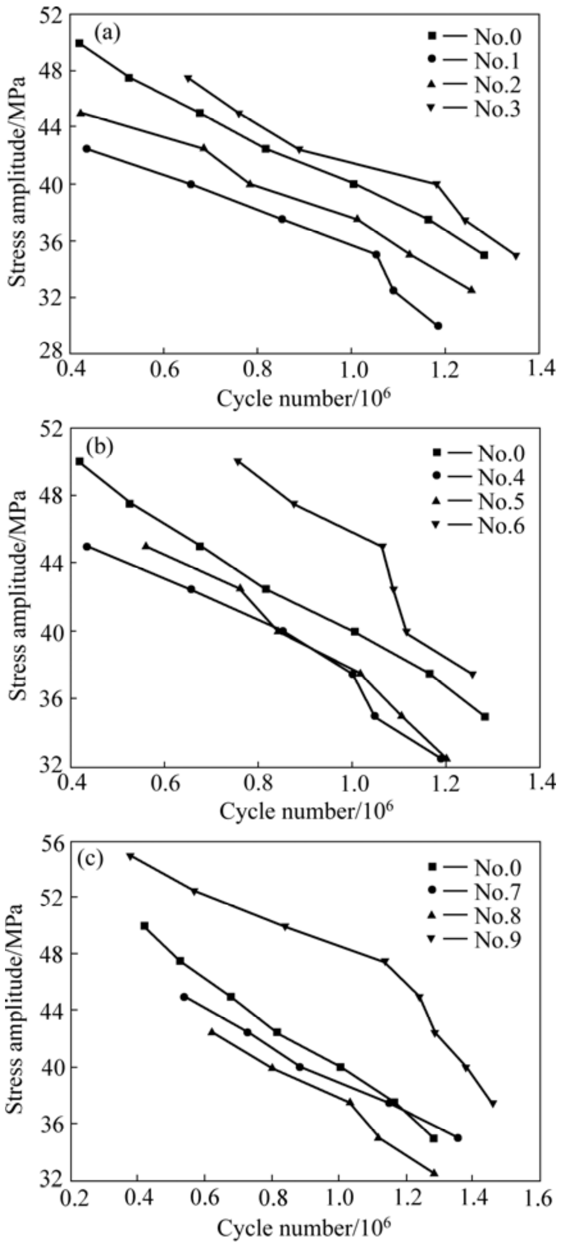

Fig. 1 Influence of elements on stress amplitude fatigue life response of alloys: (a) Specimens 0−3; (b) Specimens 4−6; (c) Specimens 7−9

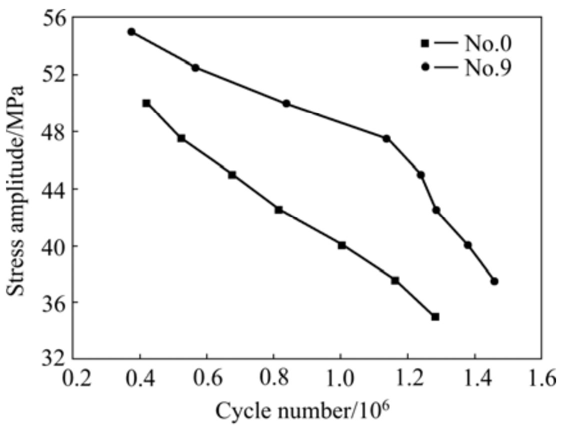

Fig. 2 Stress—cycle number curves of specimens 0 and 9

4 Analysis and discussion

4.1 Influence of alloying elements on high temperature tensile strength

In this work, the range analysis is used for studying the influence of Fe, Cu and Ni on high temperature tensile strength of alloys. K_1, K_2 and K_3 are respectively the mean of factor data in corresponding level. R is the extreme difference, namely the difference between the largest and smallest among K_1, K_2 and K_3. The larger R, the greater influence the level change of the factor on test index. For example, the one with the largest R means the influence is also the largest, and this factor is the priority to be considered in the study.

The range analysis on the influence of alloying elements for high-temperature tensile strength is shown in Table 4. It is seen that for each column of the three elements including Fe, Cu and Ni, there is $K_3>K_2>K_1$ which indicate that the high-temperature tensile strength is always increasing when Fe content varies from 0.1%→0.14%→0.28%, Cu content from 0.5%→1%→1.5% and Ni content from 0.1%→0.15%→0.2%. In this study Fe content within 0.28%, Cu content within 1.5% and Ni content within 0.2% are beneficial to increase the high-temperature tensile strength of alloys. As there is $R_{Cu}>R_{Fe}>R_{Ni}$ in the Table, this indicates that the priority sequence of influence on high-temperature tensile strength from large to small is Cu→Fe→Ni. Therefore, it is necessary to be given the priority of the influence by Cu content.

Table 4 Effects of different elements on high-temperature tensile strength of alloys

No.	w(Fe)/%	w(Cu)/%	w(Ni)/%	High temperature tensile strength/MPa
1	0.10	0.47	0.10	162
2	0.10	0.98	0.15	178
3	0.10	1.48	0.19	206
4	0.13	0.46	0.14	176
5	0.14	1.00	0.19	190
6	0.14	1.53	0.10	220
7	0.27	0.48	0.19	188
8	0.28	0.97	0.10	176
9	0.28	1.53	0.16	236
K_1	182.0	175.3	186.0	
K_2	195.3	181.3	194.7	
K_3	200.0	220.7	196.7	
R	18.0	45.3	10.7	

4.2 Influence of alloying elements on high temperature fatigue toughness

Range analysis is employed to study the influence of Fe, Cu and Ni on high-temperature fatigue toughness of Al alloy, as shown in Table 5. Seen from Table 5, the effect of alloying elements on high temperature fatigue toughness is similar to the influence of alloying elements on high temperature tensile strength. According to K_1, K_2, K_3 and R in Table 5, there is $K_3>K_2>K_1$ in the first column of Fe, the second column of Cu and the third column of Ni, which indicates that the fatigue limit is always increasing when Fe content varies from 0.1%→0.14%→0.28%, Cu content from 0.5%→1%→1.5% and Ni content from 0.1%→0.15%→0.2%, so in this study Fe content within 0.28%, Cu content within 1.5% and Ni content within 0.2% are beneficial to improve the high-temperature fatigue limit of alloys. As there is $R_{Cu}>R_{Fe}>R_{Ni}$ in the Table, this indicates that the priority sequence of influence on fatigue limit from large to small is Cu→Fe→Ni.

When Fe content is below 1%, it exists mainly in the form of bone-like Al_8SiFe_2 [18]. In the test, the actual changes of Fe are from 0.1% to 0.28%. Therefore, if Fe content is controlled within 0.28%, the higher Fe content, the more beneficial the improvement of high temperature mechanical properties of alloys.

Table 5 Effects of different elements on high-temperature fatigue limit strength of alloys

No.	w(Fe)/%	w(Cu)/%	w(Ni)/%	High temperature fatigue strength/MPa
1	0.10	0.98	0.15	35.5
2	0.10	1.48	0.19	37.8
3	0.13	0.46	0.14	41.8
4	0.14	1.00	0.19	37.8
5	0.14	1.53	0.10	38.4
6	0.27	0.48	0.19	45.2
7	0.28	0.97	0.10	38.5
8	0.28	1.53	0.16	37.8
9	38.3	37.3	39.5	48.2
K_1	40.5	38.0	41.3	
K_2	41.8	45.1	41.6	
K_3	3.5	7.8	2.1	
R	0.10	0.47	0.10	

The solubility of the nickel element in the solution of aluminum is very small, but it produces solid solution strengthening effect. In a certain range, high-temperature tensile strength increases while Ni content increase. But over the range limit, Ni and aluminum would combine together to become a large block of Ni_3Al phase, which is fragmented organization and harmful to high temperature mechanical properties. The Ref. [19] shows that when Ni content in aluminum alloy is more than 0.75% it would mainly exist as large block Ni_3Al phase which is detrimental to high temperature mechanical properties of the alloy. Al, Ni and Fe would combine to form an Al_9FeNi heat resistant phase, thereby enhancing the heat resistance of the alloy. Therefore, in this test, it is considered that the higher the Ni content, the more likely the improvement of high temperature mechanical properties of alloys, if it is controlled from 0.1% to 0.2%.

A certain amount of Cu added into the Al−Si−Mg alloy can increase the heat resistance, but different mass ratio of Cu to Mg m(Cu)/m(Mg) might affect the kinds and amounts of precipitated phases in alloy. When the ratio is more than 2.5, Al_2Cu and W ($l5Mg_8Cu_2Si_6$) strengthening phases are precipitated. The high-temperature strengthening effect of W phase is very obvious and the alloy obtains excellent high temperature mechanical properties. However, the Mg_2Si strengthening phase is unstable at high temperatures. That it aggregates easily above 185 °C results in the phenomenon of coarsening, which affects the high temperature mechanical properties of alloys. m(Cu)/m(Mg) of specimens are illustrated in Table 6.

Table 6 m(Cu)/m(Mg) of specimens

No. 0	No. 1	No. 2	No. 3	No. 4
0	1.00	2.00	3.15	1.07
No. 5	No. 6	No. 7	No. 8	No. 9
2.22	3.64	1.23	2.48	3.92

As seen in Table 6, m(Cu)/m(Mg) of specimens 3, 6 and 9 are higher among ten groups of alloy specimens, exceeding 2.5. It is clear that specimen 9 has the highest ratio, reaching 3.92. As without adding Cu, the main strengthening phase of specimen 0 at high temperatures is Mg_2Si phase, which is easy to coarsen and grow at the test temperature of 200 °C, weaken high-temperature mechanical properties of the alloy. The ratio of specimens 3, 6 and 9 are relatively large, thus more Al_2Cu and W strengthening phase precipitates, which is conducive to increasing high temperature mechanical properties of the alloy. Therefore, the high-temperature tensile strength and fatigue toughness of specimens in these groups are all higher than that of the specimen 0.

4.3 Fracture analysis

In the high-temperature fatigue tests, due to a number of fatigue fractures generated in specimens, two typical fractures are selected to have scanning electron microscopy, namely specimen 0 with the stress of 45 MPa and specimen 9 with 45 MPa, number of cycles are respectively 676000 and 1086000.

From Fig. 3, it is seen that the high-temperature fatigue fracture can be divided into three regions, namely the initiation region, propagation region and transient crack region no matter how it has more or less fatigue cycles. Fatigue cracks initiate in inclusions or defects at the specimen edges, but the propagation region of specimen 9 is larger and more obvious than that of specimen 0 because the fatigue cycle of specimen 9 is more than that of specimen 0. The transient crack region is formed by rapid expansion of the fracture in the final stage, during which the testing stress is smaller, so the transient crack region is also smaller.

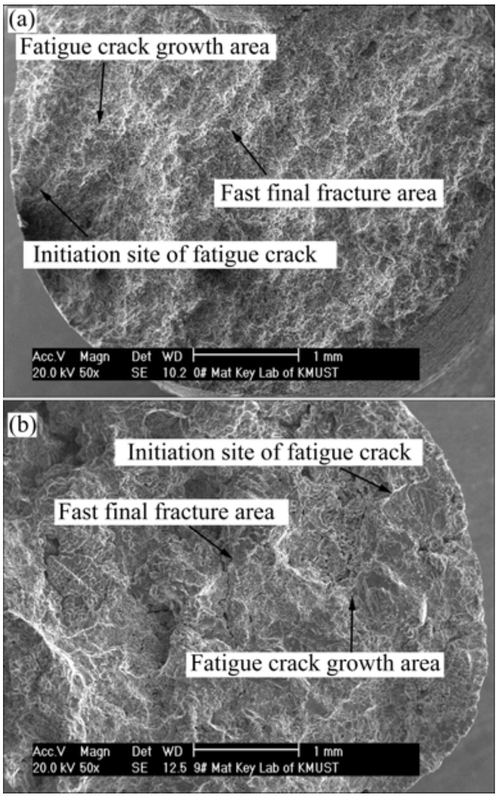

Fig. 3 Fatigue fracture surfaces: (a) specimens 0; (b) specimens 9

The initiation regions of specimens 9 and 0 are shown in Fig. 4, It is clearly seen that the fatigue initiates in casting defects at the edge of specimens, particularly at the casting pores, which are marked with black cycles in the photos. In the fatigue cycle test, it is inevitable to have defects in specimens which are more prone to produce local stress concentration during testing. Therefore, these defects will become the fracture origin and promote the fatigue crack initiation. Furthermore, casting defects in specimens reduce the time of crack initiation in high temperature fatigue test, which greatly reduces the high temperature fatigue life of alloy. As a result, it is necessary to minimize defects as much as possible during preparing specimens in order to improve the fatigue life [20].

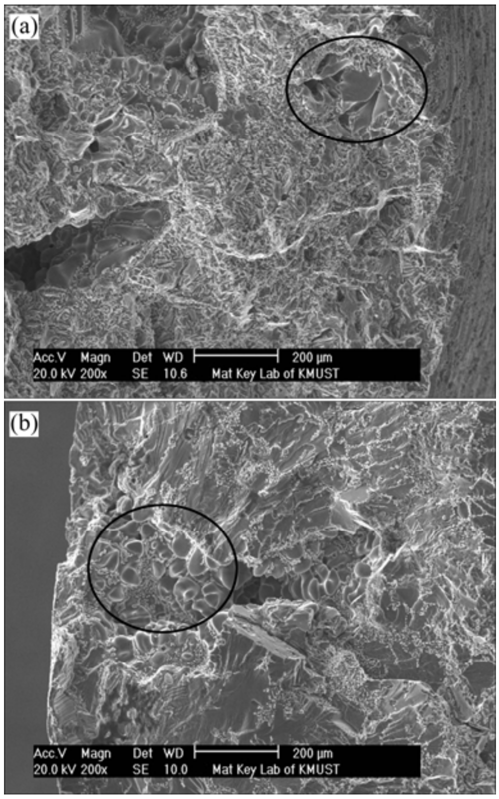

Fig. 4 Initiation sites of fatigue crack of specimens 0(a) and 9(b) at 200 °C

The propagation regions of specimens 9 and 0 are shown in Fig. 5. It is seen from Fig. 5 that the propagation regions of two specimens are significantly different: specimen 0 has obvious tear morphology and a large tear ridge with rough surface; but specimen 9 has a smooth surface with undulating hills-like morphology and obvious fatigue striations, suggesting that the specimen has repeated plastic deformations in this region.

Transient crack regions of specimens 9 and 0 are clearly demonstrated in Fig. 6, with the increased number of fatigue cycles, the tear becomes clearer and covered with a large oblique gap, which is the hole or crack left when the fracture surface is pulled out directly.

Under long-term and repetition cyclic tensile-compressive stress, there will be a cycle slip which results in slip bands. The cycle slip is very uneven and more likely distribute in the local weak areas. Then the bands gradually get larger with the increase of the cycles, which results in fatigue fracture in specimen. From Fig. 4, there are micro shrinkage cavities and blowholes at specimen edge where is relatively weak. This area is prone to have stress concentration under the action of

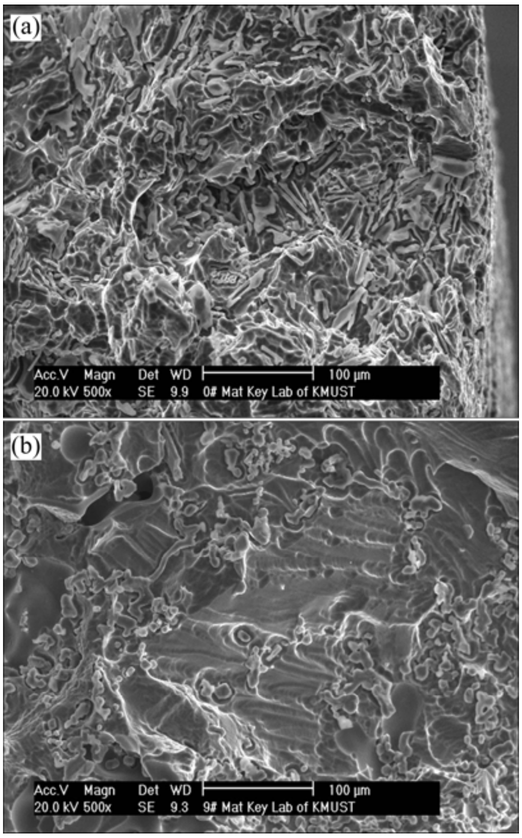

Fig. 5 Fatigue crack growth areas of specimens 0(a) and 9(b) at 200 °C

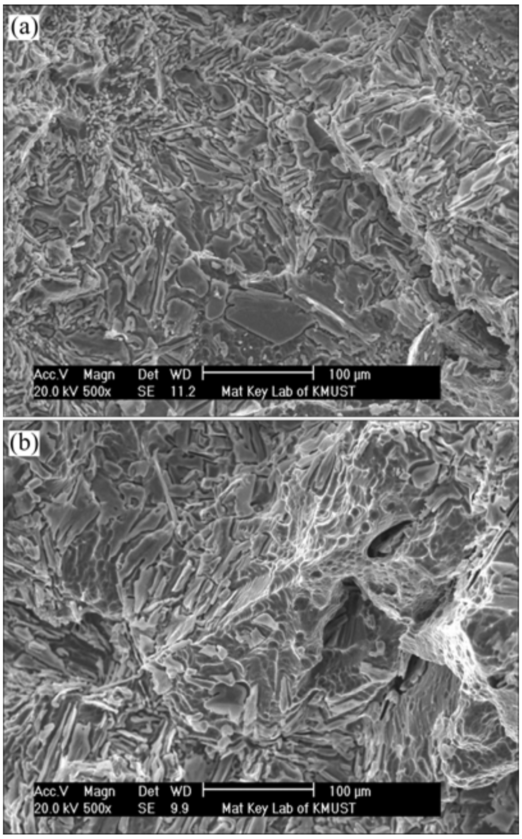

Fig. 6 Fast final fracture areas of specimens 0(a) and 9(b) at 200 °C

cyclic stress, which forms slip bands as source of micro-cracks. As the fatigue cycle continues, the micro-cracks would extend along the slip plane inwardly. When the micro-crack length reaches a certain value, its original slip line would be changed due to the role of tip stress, and then it would extend along the vertical direction with the maximum normal stress and become a larger crack. After that, the size of the crack would continue to grow and when it is over the critical size, it would lead to specimen fracture.

5 Conclusions

1) The best compositions for high-temperature mechanical performance and fatigue toughness are obtained by adding 0.07% Fe, 1.53% Cu and 0.16% Ni added into the original composition of ZL114A. The improvement is due to high mass ratio of Cu to Mg and Ni content.

2) When temperature is 200 °C, the fatigue limit of ZL114A after 106 cycles is 40.2 MPa; the fatigue limit of the specimen with the best composition after 10^6 cycles is 48.2 MPa. The mean tensile strength of both at 200 °C is 194 MPa and 236 MPa, respectively.

3) Based on the observation of fatigue fractures on ZL114A and specimen 9 through scanning electron microscope, it is found that fatigue fractures initiate on the specimen edges with casting defects, which can be reduced to improve high-temperature mechanical performance. Under the same stress level, as the cycles of specimen 9 are more than those of ZL114A, its fracture growth region is also more obvious and clear.

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