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Softening and Fatigue Fracture of Al-Si-X Alloys

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Fatigue properties of eutectic or hyper-eutectic Al-Si-Cu-Mg-(Ni, Fe, Mn) alloy casts have been studied at both 293 K and 523 K. The alloy contains primary Si crystal and/or intermetallic compounds which are coarse and hard. Those give a crack initiation site and make their fatigue strength lowered at 293 K. A linear fracture mechanics program was adopted to evaluate the ΔK of a crack. The calculated stress intensity range resulted in the modeling of fatigue crack growth by integral of the Paris equation, and then the crack propagating life, N_p, was estimated. Based on the estimation coalesced compounds gave the fatigue crack initiation site. On the other hand, ductile fracture manner was fully covered on both tensile and fatigue fracture surfaces at 523 K. Heating over at 523 K made the casts soften, and the softening resistance depended on the morphology and size of the compounds. The casts contained coarse compounds showed higher fatigue strength. Although finer dispersion of Si crystals and compounds is required to improve their mechanical properties at room temperature, acicular compounds should be remained to increase fatigue strength of the alloys at higher temperature range.

Keywords: *aluminum-silicon alloy, microstructural modification, fatigue fracture, softening*

1. Introduction

Al-Si alloys have the market share of over 90 % for die-cast materials, and big advantage of the recyclable material design as mentioned in the reference [1]. Alloying Si provides good casting properties such as small shrinkage in volume and high fluidity of molten metal. It also gives an adequate balance of lightweight, low thermal expansion and good wear resistance. To improve mechanical properties and workability of the alloy casts, microstructural modifications have been commonly achieved by the addition of Na, Ca, Ti, Zr, Sr and P into the melt or by rapid solidification. To provide an excellent balance of strength and elongation, however, the casts are processed into isothermal forging stage with hot working or repeated thermomechanical treatment [2, 3]. Furthermore, by the viewpoint of manufacturing process, as cast billet should be finer and has smooth surface. Continuous casting process with heat insulating and rapid cooling makes finer structure in casting alloys, and a billet with smooth surface due to the direct cooling with adiabatic mold [4].

On the other hand, the forged products should be equipped a high performance and precise dimension. In the case of engine piston, both high fatigue and creep strength at high temperature are required. The additions of Fe, Ni and Mn in Al-Si alloys make various morphology and size of intermetallic compounds formed in the Al-Si alloys [5]. The compounds are hard and stable at higher temperature so that it is effective to increase fatigue and creep strength, although coarsen and/or coalesced compounds lead to very poor ductility as well as primary Si crystals. Therefore the combination of developed new semi-continuous casting process [4] and precise forging process was proposed [6], since the compounds should be finely dispersed to achieve a good balance of properties.

In the present study, fatigue fracture and softening behavior of eutectic or hyper-eutectic Al-Si-Cu-Mg-(Ni, Fe, Mn) casts produced by the new method have been examined. Effects of morphology and size of Si crystals and intermetallic compounds on strength and fatigue fracture at room temperature and high temperature have been discussed.

2. Experimental

2.1 Materials

Five kinds of eutectic or hyper-eutectic Al-Si-Cu-Mg-(Ni, Fe, Mn) materials with a diameter of 80mm were produced by the continuous casting process with heat insulating and rapid cooling. The casting conditions, e.g. 185～200 mm/min of casting rate, 35L/min of cooling water rate, and casting temperature at 973K are adopted. The target chemical compositions of the casts are represented in Table 1. The test specimens were cut from the position in 1/4 radius and 1/2 radius depth of the billets.

Table 1 The chemical compositions of the alloys (mass%)

Alloys	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zr	Ti	P	Al
UTM401	14	0.15	3	-	1	-	1	0.1	0.01	0.012	Bal
UTM402	12	0.15	3	-	1	-	1	0.1	0.01	0.012	Bal
UTM403	12	0.15	3	-	1	0.1	1	0.1	0.01	0.012	Bal
UTM404	14	1	3	1	1	-	-	0.1	0.01	0.012	Bal
UTM405	12	1	3	1	1	-	-	0.1	0.01	0.012	Bal

2.2 Tensile and Fatigue Tests

The tensile test was done at 293K and 523K, with 0.5mm/min of the cross-head speed (initial strain rate=3.3×10^{-4}sec^{-1}). The uniaxial load controlled fatigue test at 293 K and 523 K was carried out with sine wave, stress ratio (minimum stress ratio/maximum stress) R of 0.01 and frequencies of 20 Hz. The microstructure and the fracture surface were analyzed by optical microscopy, and scanning electron microscopy.

2.3 Crack Generation

A linear fracture mechanics program, SCAN [7], was adopted to evaluate stress intensity factor range ΔK of a crack. The calculated stress intensity range resulted in the modeling of fatigue crack growth by integral of the Paris equation as follows:

$$\frac{da}{dN} = C(\Delta K)^m \tag{1}$$

where C and m were chosen as C=8.08×10^{-13} and m=5.03. Those were resulted from crack propagating tests of AC8A cast alloy in the reference [8]. Then the crack propagating life, N_p, was estimated by crack growth modeling. The number of cycles to failure, N_f, was determined by the fatigue tests.

2.4 Softening behavior

Vickers hardness test was done for the samples annealed at the temperatures of 473, 523, 573, 673 and 773K.

3. Result and Discussion

3.1 Microstructure of casts

Mostly fine compounds and primary Si crystals were dispersed near surface region of the billets, although primary Si crystals of several ten-micron-meter in size existed in the hyper-eutectic alloys as shown in Fig. 1. While coarse acicular compounds were not detected, globular Al-Fe-Mn compounds of several ten-micron-meter in size were segregated in the center part of the billets in UTM404 and UTM405 and were coalesced as shown in Fig. 2. For the hyper-eutectic alloy UTM404, primary Si crystals were also segregated around the compounds. Acicular eutectic compounds were also detected in the UTM404 and UTM405.

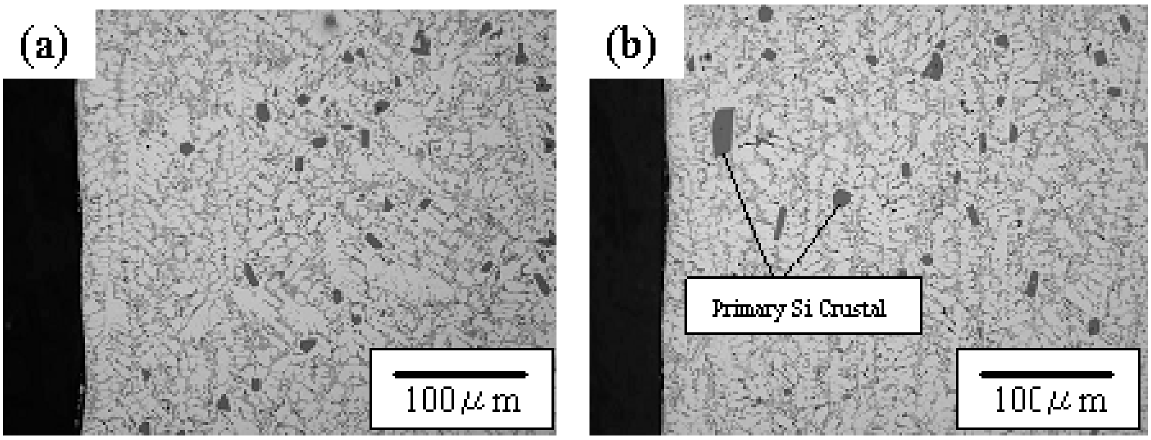

Fig. 1 Solidification structure near the surface of the billets: (a) UTM401 and (b) UTM404.

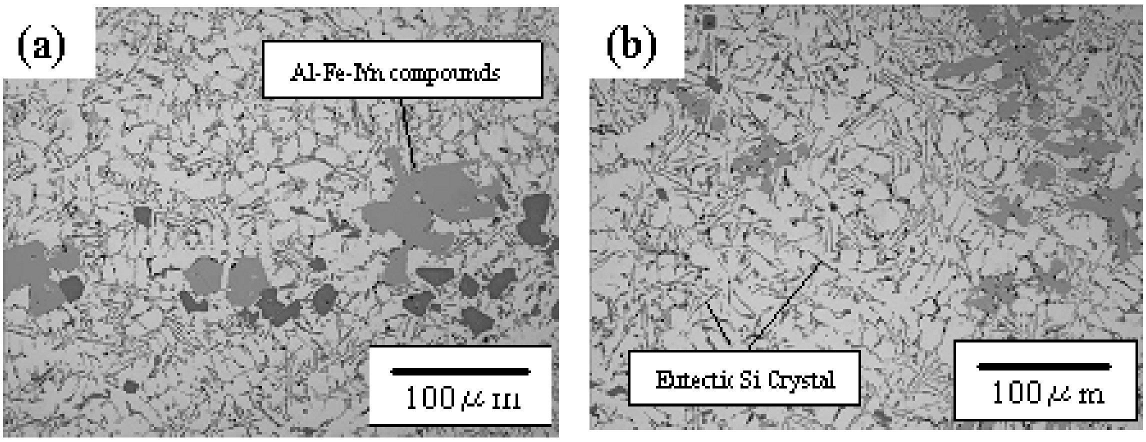

Fig. 2 Solidification structure at the center part of the billets: (a) UTM404 and (b) UTM405.

3.2 Fatigue strength and crack initiation sites

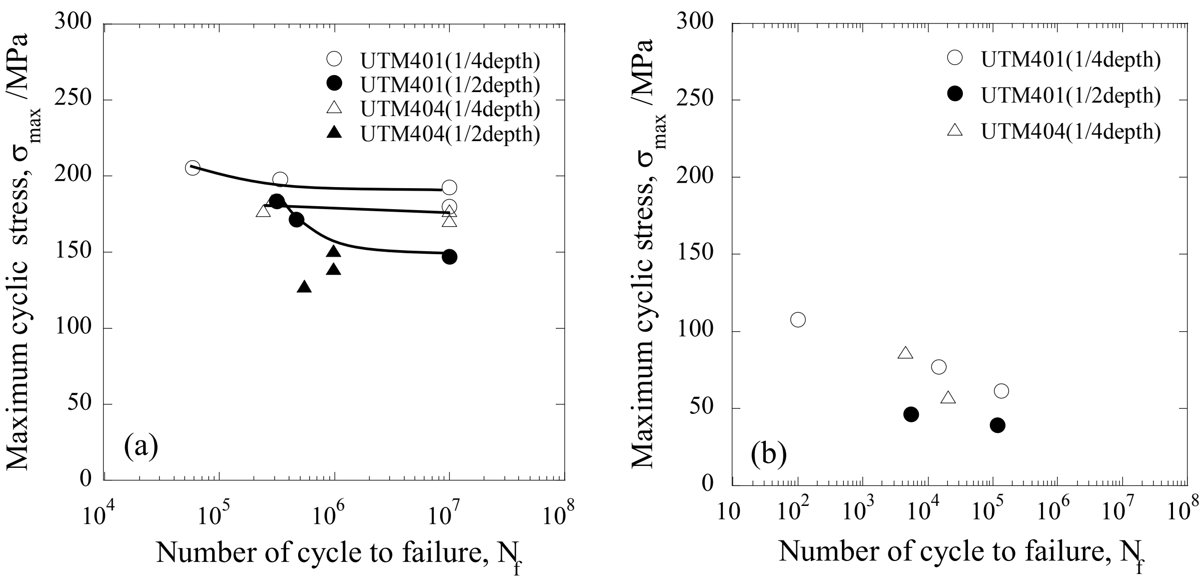

Fig. 3 S-N data for the hyper-eutectic alloys at 293 K (a) and 523 K (b).

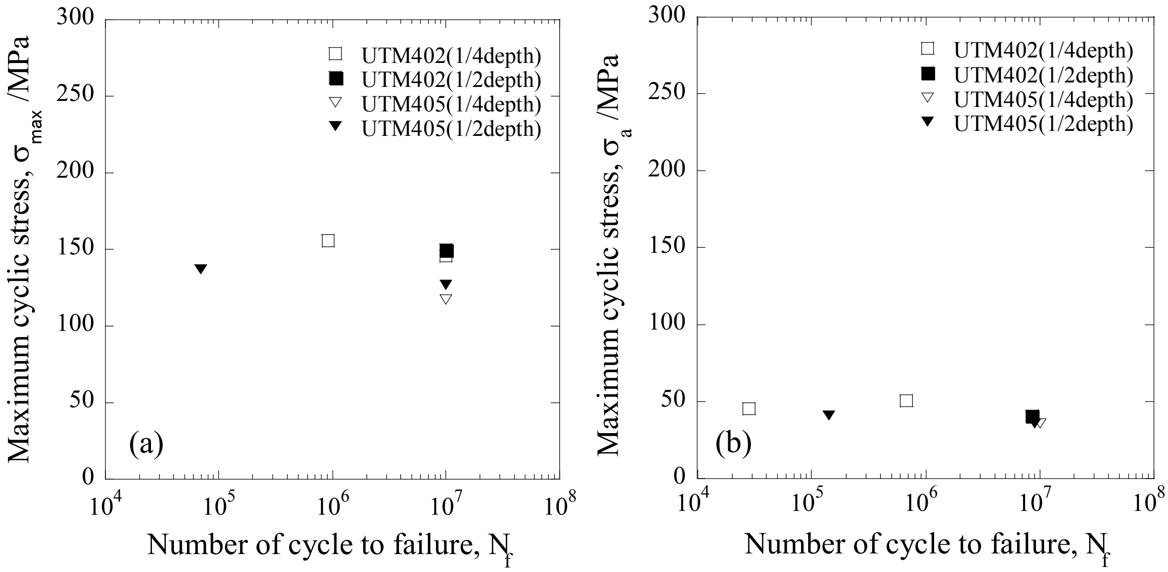

Fig. 4 S-N data for the eutectic alloys at 293 K (a) and 523 K (b).

Fig. 3 shows fatigue strength for the hyper-eutectic alloys, UTM401 and UTM404, at 293 K and 523 K. The UTM401 showed higher fatigue strength than the UTM404 at 293 K (Fig. 3(a)). Fatigue strength of UTM404 at the 1/2 radius depth was the lowest that among all test materials. The origin of its crack initiation site was the coalesced Al-Fe-Mn compounds whose size was about 150 μm as shown in Fig. 5, although primary Si crystals gave a crack initiation sites in other materials. The UTM 405 which contained the globular compounds also showed low fatigue strength at 293 K as shown in Fig. 4(a). Therefore, the segregation of compounds should be avoided and their fine dispersion may lead to improve fatigue strength in at 293 K.

Fatigue strength at 523 K was much lower than that at 293 K as shown in Figs. 3 and 4. Ductile manner such as dimple fully covered on fracture surface of the specimens failed in the low cycle range, and it can hardly detect the crack initiation site on the surface.

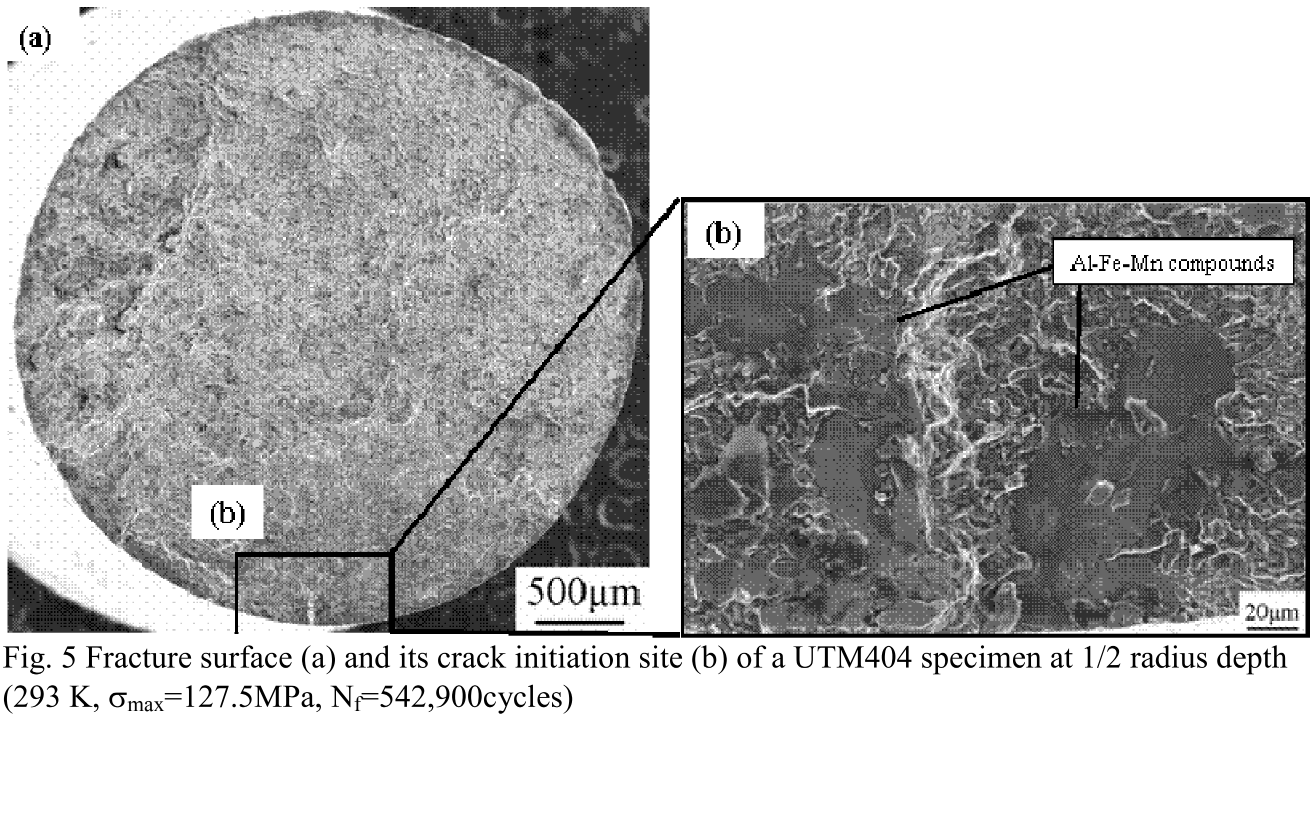

Fig. 5 Fracture surface (a) and its crack initiation site (b) of a UTM404 specimen at 1/2 radius depth (293 K, σ_{max}=127.5MPa, N_f=542,900cycles)

3.3 Softening behavior

The hyper-eutectic alloys, UTM401 and UTM404, showed higher hardness below 500 K than the eutectic ones, UTM402, UTM403 and UTM405 as shown in Fig. 6(a). Above 550 K, on the contrary, the eutectic alloys showed higher hardness than the hyper-eutectic ones. The reason why the hyper-eutectic alloys show big change of their hardness may be related with the dispersion of eutectic Si crystals. The eutectic alloys show higher volume of eutectic Si crystals than the hyper-eutectic ones. Additions of Fe and Mn were very effective to increase the hardness fully annealed above 550 K (Fig. 6(b)). No dependence of radius depth was detected for the softening behaviors in the alloys. Therefore, the size and density of primary Si crystals and compounds did not affect the hardness of fully annealed materials. Thus, fine dispersion of the compounds and eutectic Si crystals may be good for the balance of fatigue strength at high and low temperatures.

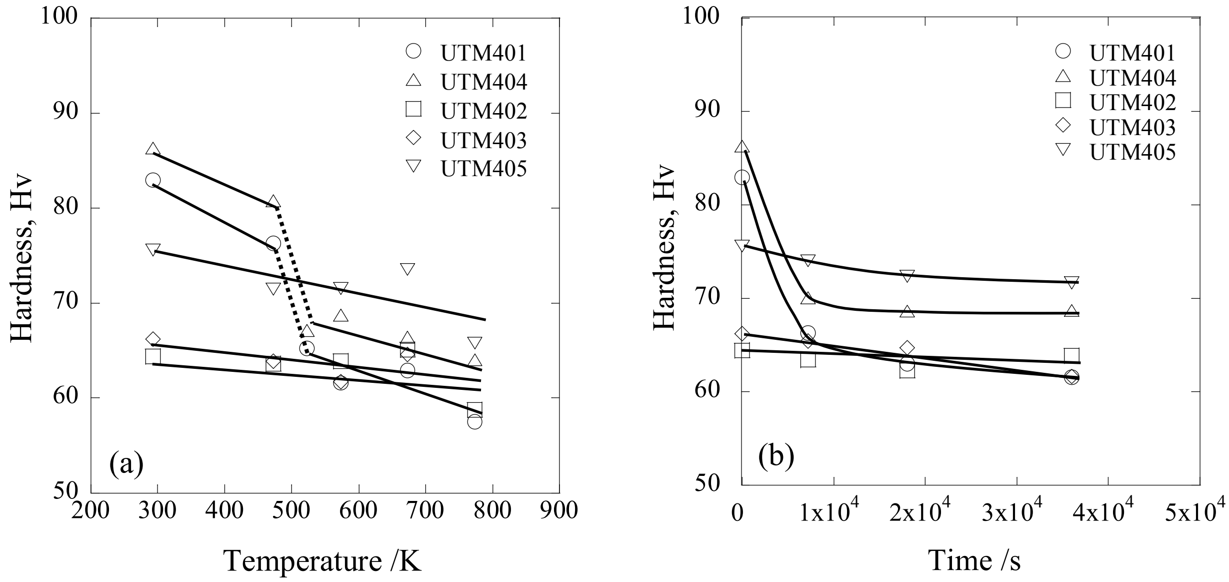

Fig. 6 Softening behavior for the alloys at 1/4 radius depth with (a) the temperatures (heating for 11 hours) and (b) heating time at 573 K.

4. Conclusions

Fatigue fracture and softening behavior of eutectic or hyper-eutectic Al-Si-Cu-Mg-(Ni, Fe, Mn) casts produced by the new method were examined. Major results were summarized as follows:

1) Coalesced Si crystals and/or compounds were still remained in the center part of the billets in hyper-eutectic alloys. Those gave a crack initiation site and made their fatigue strength lowered at 293K.
2) Ductile manner fully covered on fracture surface of the specimens fatigued at 523K.
3) Hyper-eutectic alloys containing coarse Si crystals exhibited higher hardness than eutectic alloys. However the hyper-eutectic alloys remarkably showed softening behavior over at 523 K.
4) The addition of high contents of Fe and Mn was effective to increase hardness of the alloys at high temperature.

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References

[1] O. Umezawa and K. Nagai: Trans. MRS-J 20 (1996) 190-193.
[2] O. Umezawa and K. Nagai: Metall. Mater. Trans. A, 30A (1999) 2221-2228.
[3] O. Umezawa: Materials Transactions 46 (2005) 2616-2623.
[4] H. Takagi, Y. Uetani, M. Dohi, T. Watanabe, T. Yamashita, and S. Ikeno: J. Jpn. Inst. Light Met. 58 (2008) 650-655.
[5] A. Tanihata, N. Sato, K. Katsumata, T. Shiraishi, K. Oda and O. Endo: J. Jpn. Inst. Light Met. 57 (2007) 131-136.
[6] O. Umezawa, H. Takagi, T. Sekiguchi, T. Yamashita, and N. Miyamoto: *Ceramic Transactions*, Ed. by A. Cozzi, T. Ohji, and Wiley, 207 (2009) 189-200.
[7] M. Shiratori: *Current Topics in Computational Mechanics*, Ed. by J.F. Cory, Jr. and J.L. Gordon, ASME (1995) 357-364.
[8] T. Kobayashi: J. Jpn. Inst. Light Met. 54 (2004) 333-347.