89- 20115041 Softening and Fatigue Fracture of Al-Si-X Alloy Casts

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ABSTRACT: Ductile manner such as dimple fully covered on fatigue fracture surface of the specimens at 523 K. Softening behavior of eutectic or hyper-eutectic Al-Si-Cu-Mg-(Ni, Fe, Mn) alloy casts has been examined to estimate the influence of heating on their fatigue strength at higher temperature. The hyper-eutectic alloys showed remarkable softening rather than eutectic ones. The softening during heating over 523 K may be related to Al-Cu-Mg-Si precipitation and lowered content of Cu in the matrix.

KEY WORDS: (Standardized) materials, aluminum alloy, fatigue (Free) aluminum-silicon alloys, softening, annealing [D3]

1. INTRODUCTION

Al-Si-Cu-Mg alloys are one of the major cast materials, and have good casting properties such as small shrinkage in volume and high fluidity of molten metal. Alloying Si also gives an adequate balance of lightweight, low thermal expansion and good wear resistance. Furthermore, the addition of transition metals such as Ni, Fe and Mn is expected to enhance their mechanical properties at higher temperature. However, the addition of Si and these transition metals make a coarse and brittle phase, which often give an origin of fatigue crack initiation site. In previous study, in order to refine their coarse compounds and Si crystals, the casts were processed into isothermal forging stage with hot working or repeated thermomechanical treatment.[1), 2)] Although this process provided an excellent balance of strength and elongation, a few of large Si crystals were still remained in the specimens, and it gave a crack initiation site. Since microstructure of as-cast materials significantly influence to the refinement of second particles, the cast materials must be applied to rapid solidification. A continuous casting process with heat insulating and rapid cooling can achieve a refinement of microstructure with smooth surface of cast billet.[3)] The cast shows advantages on producing forged product such as good formability, less cutting of material, near-net forming, lower working temperature etc.[4)] However, fatigue strength at 523 K was much lower than that at 293 K.[5)] Although large primary Si crystal or coalesced intermetallic compound were selected as an origin of crack initiation site for the specimens failed at 293 K, ductile fracture manner such as dimple fully covered on fatigue fracture surfaces of the specimens failed in the low cycle range at 523K. Thus, softening behavior of their casts has been examined to estimate the influence of heating on their strength. In this study, fatigue properties and softening behavior of eutectic or hyper-eutectic Al-Si-Cu-Mg-(Ni, Fe, Mn) alloy casts have been studied.

2. FATIGUE PROPERTIES

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. In addition, all specimens contain 0.1mass%Zr, 0.01mass%Ti and 0.012mass%P. 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 test alloys (mass%)

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

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. In contrast to the microstructure of UTM402, UTM403 contained several coarse primary Si crystals due to effect of Cr addition. 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. 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.

2.2. Tensile and Fatigue Tests

The tensile test was done at 293 K and 523 K with 0.5 mm/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 scanning electron microscopy.

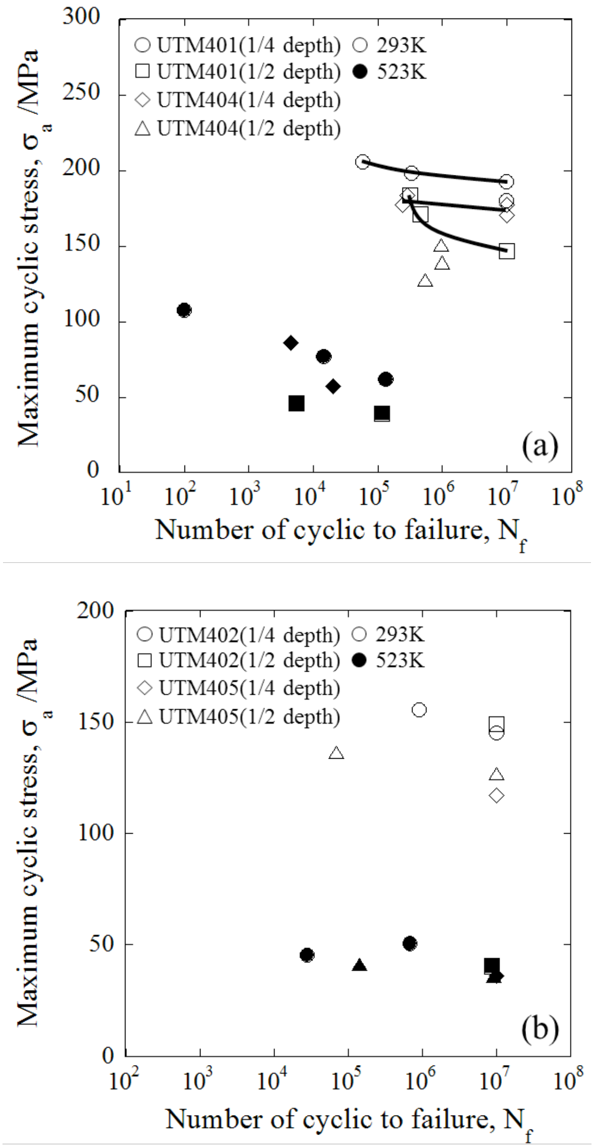

Fig. 1 S-N data at 293 K and 523 K for (a) the hyper-eutectic alloys, and (b) the eutectic alloys.

2.3. S-N data

Figure 1 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. Fatigue strength of UTM404 at the 1/2 radius depth was the lowest that among all test materials at 293 K. The origin of its crack initiation site was the coalesced Al-Fe-Mn compounds whose size was about 150 μm, although primary Si crystals gave a crack initiation sites in other materials. The UTM405 which contained the globular compounds also showed low fatigue strength at 293 K as shown in Fig. 1(b). Therefore, the segregation of compounds should be avoided and their fine dispersion may lead to improve fatigue strength at 293 K.

Fatigue strength at 523 K was much lower than that at 293 K. Although data were limited, there was no big difference of fatigue strength at high cycle range among the alloys at 523 K.

3. SOFTENING BEHAVIOR

3.1. Fatigue fracture surface

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. Thus, softening in the casts during heating at the temperature may affect their fatigue strength and fracture manner.

3.2. Softening of alloys by annealing

The alloys were annealed at the temperatures of 473, 523, 573, 673 and 773 K, and cooled in a furnace. Vickers hardness in the matrix was evaluated for the samples. The hyper-eutectic alloys, UTM401, showed higher hardness below 500 K than the eutectic ones, UTM402 as shown in Fig. 2(b). Above 550 K, on the contrary, the hyper-eutectic alloys showed remarkable softening, and almost the same hardness as that of the eutectic ones. Additions of Fe and Mn were very effective to increase the hardness fully annealed above 550 K (Fig. 2(a)). There was no big difference of the optical microstructure between as-cast materials and annealed materials. No dependence of radius depth was detected for the softening behaviors in the alloys, either. Therefore, the morphology and size of Si crystals and compounds did not affect the hardness of fully annealed materials. The reason why the hyper-eutectic alloys showed big change of their hardness may be related with the matrix softening. Thus, not only fine dispersion of the compounds and eutectic Si crystals but also the solute strengthen in the matrix may be good for the balance of fatigue strength at high and low temperatures.

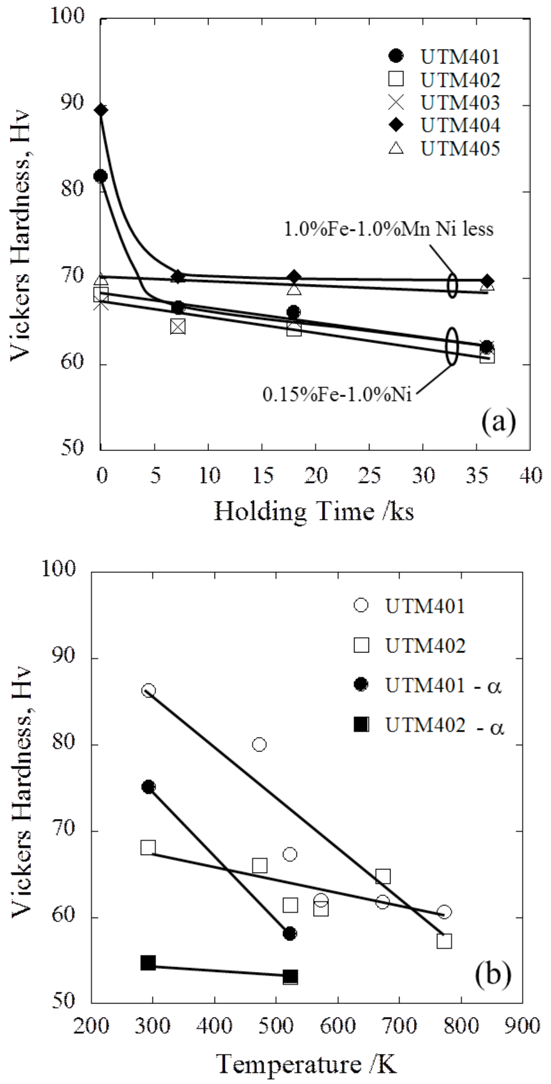

Fig. 2 Softening behavior for the alloys at 1/2 radius depth (a) at 573 K and (b) at temperatures with heating for 11 h.

4. MICROSTRUCTURAL ANALYSES

4.1. Precipitation during annealing

X-ray diffraction (XRD) analysis and electron probe microanalysis (EPMA) were carried out to identify intermetallic compounds dispersed in the matrix. Figures 3 and 4 show backscatter electron images of the alloys of UTM401 and UTM402 annealed at 523 K for 11 hours, respectively. Fine Al-Cu-Mg-Si acicular compounds of several hundred-nanometer in size were detected in the matrix of UTM401 (Fig. 3), although no peaks of Al-Cu-Mg-Si compounds were detected on XRD profile for as-cast material. On the contrary, no precipitates were detected in the matrix of UTM402.

Figure 5 shows solute contents of Si, Cu and Mg in the matrix for the as-cast materials of UTM401 and UTM402. The UTM401 exhibits higher solute contents in the matrix than the UTM402. The solutes of Cu and Mg give the solute hardening in the matrix as well as fine precipitation hardening. If these solutes are exhausted as forming coarse precipitates by annealing, hardness in the matrix should be lowered.

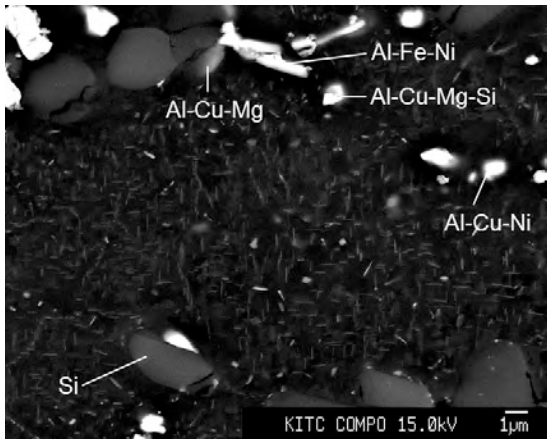

Fig. 3 Backscatter electron image of UTM401 annealed at 523 K for 11 h.

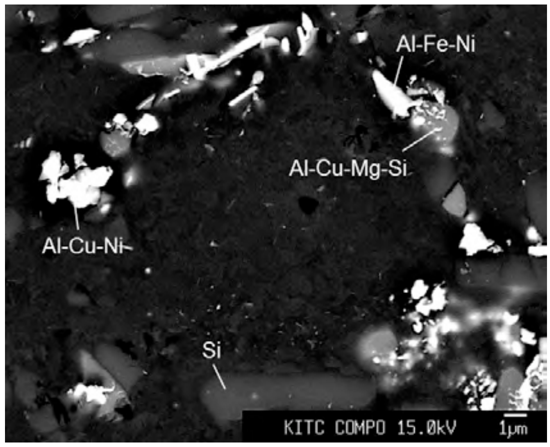

Fig. 4 Backscatter electron image of UTM402 annealed at 523 K for 11 h.

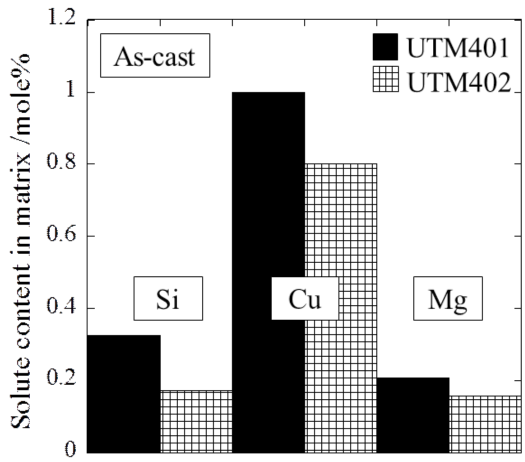

Fig. 5 Solute content in the matrix for UTM401 and UTM402.

Therefore, the softening by heating over 523K in the hyper-eutectic alloys may result from lower solutes content in the matrix due to precipitating Al-Cu-Mg-Si coarse compound.

4.2. Quasi-binary phase diagram

In order to estimate equilibrium phase in the specimens annealed, quasi-binary phase diagram was thermodynamically calculated. The equilibrium phases in the UTM401 and UTM402 at 293 K were α−Al, Si crystal, $Al_9(Fe,Ni)_2$, Al_7Cu_4Ni, and $Al_5Cu_2Mg_8Si_6$. Although Al-Cu-Mg compounds were detected in the as-cast material of UTM401, it was available at below 0.9 mass%Si content. When primary Si is rapidly solidified from liquid metal of the hyper-eutectic alloys, the content of Si in the liquid around the Si crystals is lower than that in the equilibrium condition. In the case of rapid solidification, α-Al phase around primary Si crystals is produced with less Si diffusion, so that the content of Si in the α-Al may be lower than blow 0.9mass%Si.

Quasi-binary phase diagram for the Al-Si alloy containing 3.0 Cu, 1.0 Mg, 1.0 Ni and 0.15 Fe in mass% was calculated with the range of 0 - 2 mass%Si content. Al-Cu-Mg compound was formed in lower content of 0.9 mass%Si. Fine precipitates of Al-Cu-Mg give a hardening in the matrix. After fully annealing, however, the precipitates in the hyper-eutectic alloys were coarsened to the Al-Cu-Mg compound of several ten-micro-meter in size so that the softening for the hyper-eutectic alloys occurred.

CONCLUSIONS

1. Ductile fracture manner fully covered on fracture surface at 523 K, and it may reflect on the alloy softening.
2. The additions of Fe and Mn were effective to increase hardness of the Al-Si-Cu-Mg alloys at high temperature.
3. Fine acicular compounds of enriched Mg-Si-Cu were detected in the matrix of the hyper-eutectic alloy annealed at 523 K. It may cause the softening behavior.
4. Al-Cu-Mg compounds were existed in as-cast material of UTM401. Softening for the hyper-eutectic alloys may be also related to coarsening of its compounds.

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