

MECHANICAL PROPERTIES AND ELECTRICAL CONDUCTIVITY IN SOLUTION TREATED Al-Fe-Co ALLOYS

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ABSTRACT The effects of adding Co to an Al-Fe alloy used for heat exchangers, specifically the effect on the material's tensile strength and its electrical conductivity, have been investigated. It was found that the tensile strength increased considerably while its electrical conductivity did not degrade as much as in Al-Mn alloys. The increase of strength result from finer grain size and dispersion strengthening owing to Al-Fe-Co precipitates. The small decrease in electrical conductivity is due to the slight change of solution element fraction in the matrix caused by Co addition.

Keywords: *Al-Ni-Co alloys, mechanical strength, electrical conductivity, heat exchanger, brazing, recrystallization*

1. INTRODUCTION

Aluminum alloys are widely used in heat exchangers because the materials have a high specific strength and good thermal conductivity. Heat exchangers made of aluminum alloys are usually manufactured by a brazing process using Al-Si filler alloys. In this process, the materials are heated up about 823 K. Conventional materials for heat exchangers are Al-Mn system alloys (3000-series) which have a relatively high melting temperature and a high mechanical strength. Since brazing process acted on materials as a kind of solution testament and this process would lead to dissolution of Mn in Al matrix, thermal conductivity of the alloys is low in comparison with commercial pure aluminum and Al-Fe system alloys.

Therefore, a favorable combination with high heat conductivity and high strength are required for an aluminum alloys used as heat exchangers. The present authors pay more attention to precipitation and dispersion strengthening than the other strengthening. Since they are effective by addition of elements having a small amount of maximum solid solubility within aluminum in order to strengthen the kind of materials. For instance, many investigations of Fe addition to commercial pure aluminum were performed,^{1, 2)} because the maximum solubility in Al-Fe binary alloy is less than 0.05 at%.³⁾ Hence, the strength of Al-Fe alloys is less than that of Al-Mn alloys. Since the maximum solubility in Al-Co binary alloy is less than 0.02 at%,^{4, 5)} we have found that an increase of Co content in Al-Fe-Co alloys increased the mechanical strength without reducing thermal conductivity as much as in Al-Mn alloys. This paper studies the improvement of both strength and thermal conductivity in Al-Fe-Co alloys, by addition of Co though a precipitation and dispersion strengthening.

2. EXPERIMENTAL PROCEDURE

The chemical composition of the specimens is shown in Table 1. Alloys of No.1 to No.4 are the Al-Fe alloys with different Co concentrations, and alloy of No.5 is Al-Mn alloy (3000- series). These alloys were prepared by melting and mold casting to an ingot with 60 mm thickness, followed by planing both faces to reduce the thickness down to 50mm. They were homogenized at 773K,

and hot-rolled to a thickness of 3.5mm. Then, they were cold-rolled to the prescribed thickness, and they were annealed at 553K for 2 hours. The annealing samples were cold-rolled to the final thickness of 0.1mm. Amount of final cold-rolling ratio was varied between 5-40%. Finally, the specimens were heated in a nitrogen atmosphere at 873K for 3.5 minutes which simulates brazing treatment.

Tensile tests were performed using an Instron-type material testing machine at a strain rate of $8.3 \times 10^{-4} \text{ s}^{-1}$. Electrical conductivity was measured by the four-terminal method in which the specimens were set in an oil bath at 293K. In this study, electrical conductivity is an indication of thermal conductivity, because electrical conductivity is in a linear relationship with thermal conductivity at a fixed temperature. Observation of the recrystallized grain size was carried out by an optical microscope. Scanning-electron microscope (SM-300 SEM) and transmission-electron microscope (EX-3010 TEM) were used to characterize the microstructures. Meanwhile, compositions of the matrix and small particles were examined by energy dispersive X-ray (EDX) analysis system with SEM and TEM.

Table 1 Chemical composition of specimens (mass%)

NO.	Si	Fe	Co	Zn	Mn	Cu	Al
1	0.50	0.95	0.00	1.00	-	-	bal. Al-0%Co
2	0.52	0.91	0.28	1.00	-	-	bal. Al-0.3%Co
3	0.57	0.95	0.47	1.02	-	-	bal. Al-0.5%Co
4	0.55	0.95	0.94	1.02	-	-	bal. Al-1.0%Co
5	0.25	0.60	-	1.50	1.10	0.15	bal. Al-Mn

3. RESULTS AND DISCUSSION

3.1 Tensile strength and electrical conductivity in Al-Fe-Co alloys

Figure 1 shows tensile strength, yield strength and elongation of specimens treated with a final cold rolling ratio of 40%. The tensile strength and yield strength increase while the elongation decrease, with the addition of Co. In particular, the tensile strength for Al-1.0%Co are 115 MPa, being same as that of Al-Mn alloy.

The results shown in Figure 2 are the electrical conductivity of specimens. Although the electrical conductivity decreases slightly with increasing Co, they keep at a level around 51 ~ 54% IACS. On the other hand, the electrical conductivity of Al-Mn alloy is 37% IACS, which is a much lower value than that in Al-Co alloys.

The Al-Mn alloy is high in strength but low in electrical conductivity, while the Al-0%Co alloy is low in strength but high in electrical conductivity. The addition of Co to Al-Fe alloys remarkably improved the tensile strength without clear decrease in electrical conductivity. Thus, Al-Fe-Co alloy has an almost same strength as Al-Mn alloy and shows considerably higher electrical conductivity.

3.2 Effects of Co addition on Al-Fe alloy

The results in Fig. 3 show the crystal grain size of specimens treated by final cold-rolling with various ratios after annealed at 873K. As shown in Figure 3, the grain size decrease largely by cold-rolling for all alloys. As the same rolling ratio, the grain size furthermore decreases by addition of Co. The increase of final cold-rolling ratio leads to the increase of dislocation density, nucleated sites and driving forces for recrystallization. Clearly, the addition of Co brings about the increase in nucleated sites which promotes the formation of fine-grained structure. The reduction in grain size due to Co addition is possibly caused by an increase of crystallized phases.

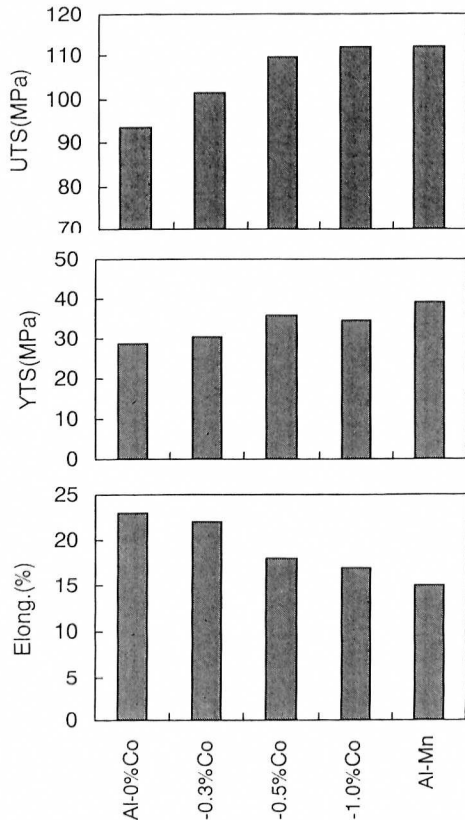


Fig. 1 Mechanical properties of Al-Fe-Co sheet specimens.

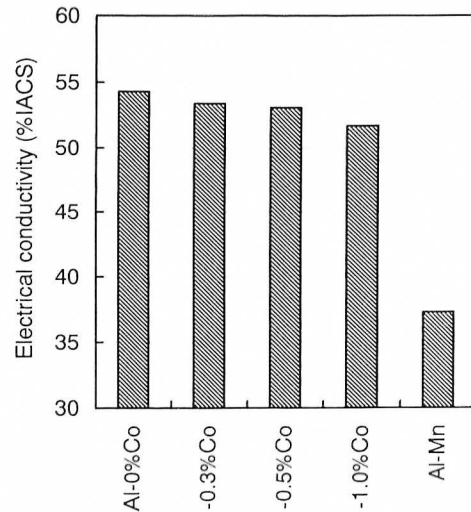


Fig. 2 Electrical conductivity of sheet specimens.

The relationship between tensile strength and grain size is shown in Figure 4, where the axis is scaled to be $d^{-1/2}$. The strength has a linear relation to the grain size. The best-fit curve in Figure 4 has the same gradient for all alloy, being satisfying Hall-Petch relation. This indicates that the strengthening mechanism is interpreted as the improvement of interaction between dislocation and grain boundaries. However, the strength increases due to the addition of Co at the same grain size $d^{-1/2}$ except in Al-1.0%Co alloy. Therefore, it is understood that strength increase by Co addition is not only a result of the reduction in crystal grain size.

Observed distribution of the particles of crystallized phases with final cold-rolling ratio of 10% is shown in Figure 5. The number of crystallized phase increases as the Co addition increases. There are a large amount of the crystallized phase with the size less than $3 \mu\text{m}$ for Al-0.3%Co and Al-0.5%Co alloy. There are a small amount of crystallized phases in Al-1.0%Co alloy. However, the size of crystallized phases in Al-1.0%Co alloy is much larger than that of the other alloys, the largest size is more than $10 \mu\text{m}$. Al-1.0%Co alloy differs from the other alloys in the distribution of crystallized phase. It is presumed that the distribution of the crystallized phase of each alloy directly change the strength.

Figure 6 shows the results of EDX analysis of the crystallized phases in Figure 5. The crystallized phases in the Al-0 %Co alloy is an Al-Si-Fe compound, and these in Co-added alloy is an Al-Si-Fe-Co compound with the least trace in an Al-Si-Fe compound. Since the peak intensities for both Al-0.3%Co and Al-0.5%Co alloys in Figure 6 are almost the same, they are presumably compounds of nearly the same composition.

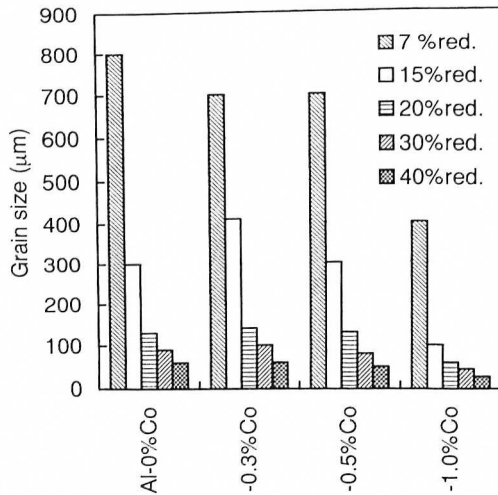


Fig. 3 Relationship final cold rolling ratio and grain size.

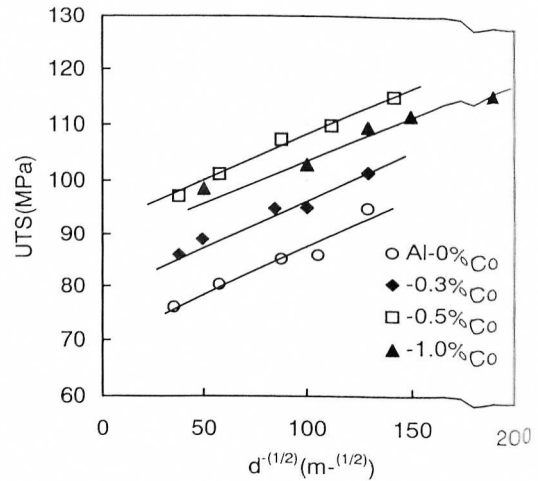


Fig.4 Relationship grain size and tensile strength.

On other hand, since the peak intensity of Co for Al-1.0%Co are much larger than the peak intensity of Fe, the composition of the compound in Al-1.0%Co is different from Al-0.3%Co and Al-0.5%Co alloys. Possibly the fact that crystal grain size became smaller through the increase of Co as shown in Figure. 5 is related to the fact that the number of the nucleated site increase through the increase of crystallized phases fraction and their size.

Figure 7 shows TEM micrograph of the selected specimen at final cold-rolling ratio of 20% in order to study its precipitation behavior. As shown in Figure 7, Al-0%Co, Al-0.3%Co and Al-0.5%Co have a dispersion of precipitates smaller than 1 μm in size, and the precipitate fraction increases with increasing Co addition. The compositions of matrix and precipitates have been examined by EDX analysis in Fig. 7 and are given in Table 2. The main elements contained in the matrix are Si and Zn, whereas Fe and Co remain under the detection limit of EDX. Therefore, it is believed that precipitation strengthening caused by the increase in volume fraction of Al-Si-Fe-Co precipitation results from Co addition. Furthermore, little change is seen in the composition of the matrix caused by Co addition. This is probably due to the fact that the maximum solubility of Co is fixed around 0.02at%. This interpreted that the electrical conductivity did not change significantly with Co contents. The strength reflects the size and volume fraction of particles dominated by the Co contents, whereas electrical conductivity represents the similar composition of the matrix which is regardless to the Co-addition.

Table 2 the compositions of matrix and precipitates of specimens (at%)

Alloy	matrix					precipitates				
	Al	Si	Fe	Co	Zn	Al	Si	Fe	Co	Zn
Al-0%Co	99.28	0.32	0.00	0.00	0.40	77.64	6.61	15.48	0.00	0.27
Al-0.3%Co	98.95	0.51	0.07	0.02	0.45	76.32	9.51	8.96	5.13	0.07
Al-0.5%Co	98.78	0.57	0.06	0.00	0.58	76.5	7.88	9.90	5.65	0.07
Al-1.0%Co	99.09	0.45	0.00	0.04	0.42	80.09	4.00	7.67	8.24	0.00

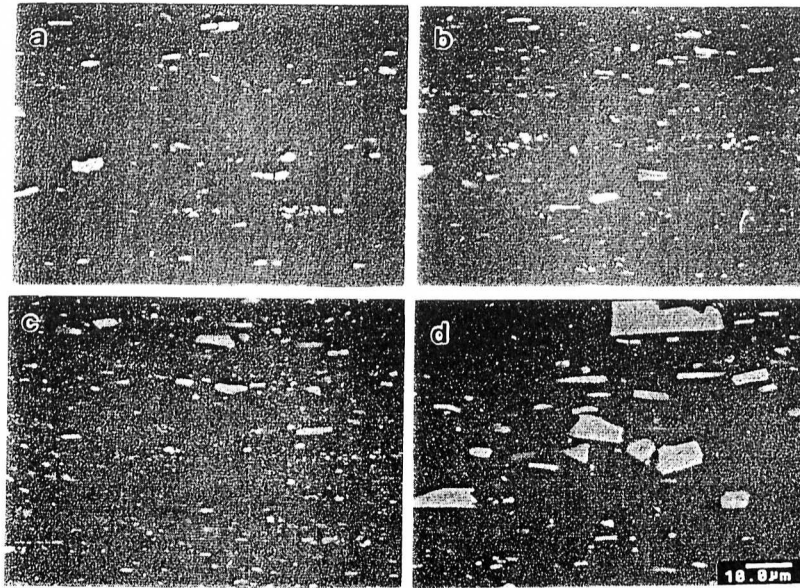


Fig. 5 SEM structures of sheet specimens. a)Al-0%Co, b)Al-0.3%Co, c)Al-0.5%Co, d)Al-1.0%Co.

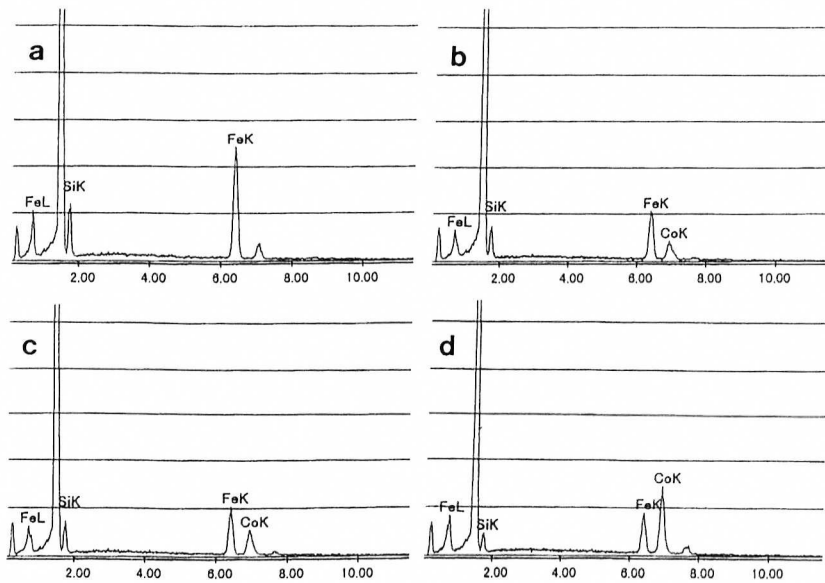


Fig. 6 EDX analyses of crystallized phases in sheet specimens. a)Al-0%Co, b)Al-0.3%Co, c)Al-0.5%Co, d)Al-1.0%Co.

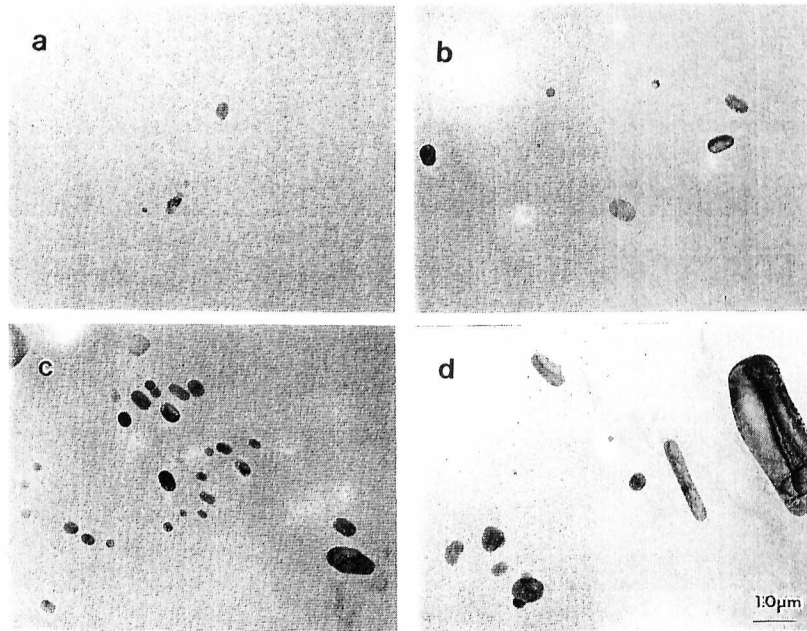


Fig. 7 TEM structures of sheet specimens. a)Al-0%Co, b)Al-0.3%Co, c)Al-0.5%Co, d)Al-1.0%Co

4. CONCLUSION

Regarding materials for heat exchangers, the effects of Co addition in Al-Fe alloys on their mechanical strength and electrical conductivity have been investigated in order to improve both strength and heat conductance of the alloys. It was found that mechanical strength increased considerably by adding Co, while electrical conductivity did not change too much. The increase in strength was attributed to both dispersion strengthening owing to Al-Si-Fe-Co precipitates, and finer grain caused by the increase of crystallized phases fraction. The small decrease in electrical conductivity is due to the slight change of solution element fraction in the matrix caused by Co addition. The present specimens shows better properties for heat exchangers, in comparison with Al-Mn

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