THE INFLUENCE OF MICROSTRUCTURE ON THE BENDABILITY OF Al-Mg-Si ALLOYS

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ABSTRACT The influence of microstructure on the bendability of Al-Mg-Si alloys has been studied. A large number of precipitates on the grain boundaries tend to decrease the bendability of the alloys by promoting the initiation and propagation of the cracks at the grain boundaries during bending. The bendability was explained as a function of precipitate distribution on the grain boundaries and yield strength. The effect of alloy composition on the bendability was also discussed.

Keywords: *Al-Mg-Si alloys, bendability, microstructure, grain boundary precipitates*

1. INTRODUCTION

In recent years, aluminum alloys have been used in automotive body panels for the purpose of their weight reduction. Heat treatable Al-Mg-Si alloys are often used for outer panel applications since they have paint bake hardenability, and no stretcher-strain marks, and so forth. But the bending performance of Al-Mg-Si alloys are sometimes inadequate for flat hemmed parts applications. There has been few works about the bendability of Al-Mg-Si alloys [1,2], but the correlation between the bendability and material properties has been studied little [3,4] and is unclear in many respects. This study has investigated the influence of microstructure on the bendability of mainly excess-silicon type Al-Mg-Si alloys often used as practical alloys.

2. EXPERIMENTAL PROCEDURE

Alloys with the chemical compositions listed in Table 1 were melted, hot rolled, cold rolled to 1mm thick sheets, and tested.

Table 1 Chemical composition of alloys (mass%)

alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
A	0.83	0.12	-	0.06	0.89	0.03	<.01	0.02	bal.
B	0.71	0.12	-	0.05	0.74	0.04	<.01	0.01	bal.
C	0.70	0.12	-	0.08	0.69	0.04	<.01	0.01	bal.
D	0.79	0.12	0.70	0.05	0.74	0.04	<.01	0.01	bal.

Each cold-rolled sheet was recrystallized by annealing in a salt bath at 540℃ for 1 min at first and then solution treated by holding in the temperature range of 460℃ to 560 ℃ for 1 min and quenching into water. Specimens of different strength were prepared by subsequent aging at 25 and 100℃. Bend test specimens were pre-strained in order to meet the conditions of pressed panels (up to 10%) and then bend tested through 180 degrees to an inner thickness of 1.0 mm. The bend test specimens were treated to reveal fine cracks and were visually classified on a five-point scale according to the size and number of the cracks. The cracks found on the tension surface of the bent specimens were examined by optical microscopy (OM) and scanning electron microscopy (SEM). Microstructure of the specimens were observed by transmission electron microscopy (TEM). Thin foils for TEM observation were made by the electrolytic polishing method.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Characterization of cracks formed in bend test specimens

The alloy A solution treated at 510℃ and subsequently aged at 25℃ was bend tested. Fig.1 shows OM micrographs of the cross section of the bend test specimens and SEM micrographs of the tension surface. More cracks were found in the more pre-strained specimen. The OM micrographs show that cracks are intergranular ones. From the SEM micrographs, the fracture surfaces seem to be the ductile type and relatively many precipitates are observed on their surfaces (arrowed).

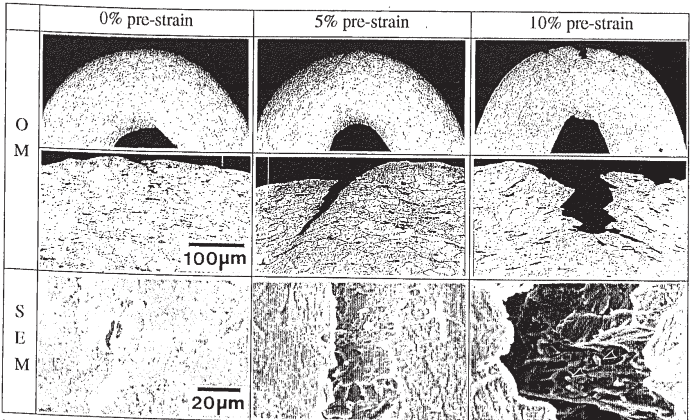


Fig.1 OM and SEM micrographs of the bend test specimens of the alloy A solution treated at 510℃.

Fig.2(a) shows the bright field TEM micrograph of the alloy A solution treated at 510℃ and aged at 25℃. Large number of precipitates are observed on the grain boundaries. Fig.2(b) shows the x-ray energy-dispersive spectroscopy (EDS) spectrum of the typical ones. These precipitates are presumed to be magnesium silicide (Mg_2Si) and Si, since the Al peaks are attributable to the matrix and O peaks are artifacts by electrolytic polishing. Fig.3 shows the bright field TEM micrograph of the alloy A solution treated at 540℃ and aged at 25℃. The solution treatment at 540℃ provides the alloy A with better bendability than that at 510℃. The grain boundary precipitates are not recognized as significantly as in the alloy A solution treated at 510℃. Mg_2Si and Si phases densely distributed on the grain boundaries presumably facilitated the initiation of cracks at the grain boundaries and accelerated the propagation of cracks along the grain boundaries.

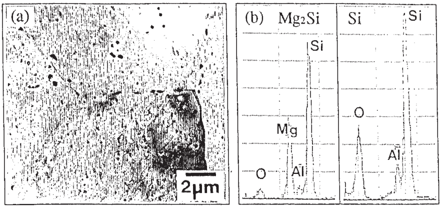


Fig.2 TEM micrograph of the alloy A solution treated at 510℃ (a) and EDS analysis of the typical precipitates on the grain boundaries(b).

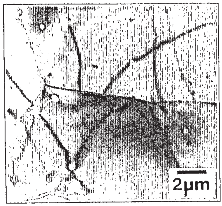


Fig.3 TEM micrograph of the alloy A solution treated at 540℃.

3.2 Precipitation behavior on the grain boundaries

These grain boundary precipitates are thought to have formed during or after the solution treatment. The precipitation behavior on the grain boundaries at various temperatures was investigated by using the alloy A. The alloy A was fully solution treated at 550℃ for 1h, quenched into water, held at 200 to 540℃ for 1 h to bring about precipitation, and observed by TEM. Bright field TEM micrographs of the specimens are shown in Fig.4.

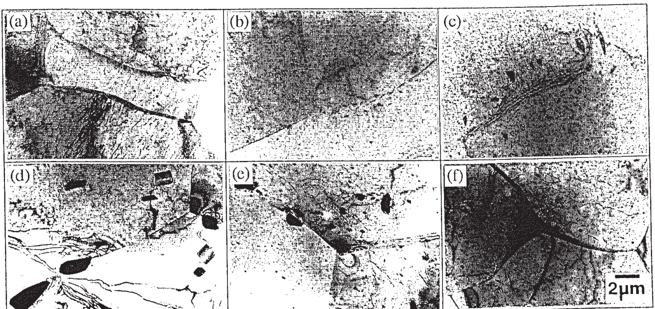


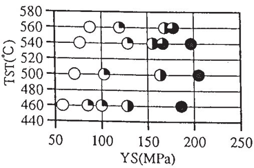
Fig.4 TEM micrographs of the alloy A solution treated at 550℃ for 1h(a), and successively held at 200℃(b), 295℃(c), 400℃(d), 510℃(e), and 540℃(f) for 1 h.

Insoluble intermetallic compounds containing Fe, Mn and so forth are present, but no particular precipitates on the grain boundaries is recognized in the specimen as solution treated at 550 ℃ (Fig.4(a)). In the specimen held at 295 ℃, the precipitation of Mg_2Si and Si phases on the grain boundaries is evident (4(c)). This tendency becomes conspicuous in the specimen held at 400 ℃ (4(d)). In the specimen held at 510℃ (4(e)), the grain boundary precipitates are observed, but in smaller numbers. In the specimen held at 540℃(4(f)), the amount of grain boundary precipitation is reduced further. These results show that the grain boundary precipitation in the alloy A occurs markedly in the neighborhood of 400℃ and diminishes as the temperature increases to expand the solubility limit of solute atoms. The grain boundary precipitates that adversely affect bendability seem to be formed as follows: during incomplete solution treatment or on subsequent cooling, a complete α single phase was not obtained and over-saturated solute atoms precipitated as the Mg_2Si and Si phases on the grain boundaries.

3.3 Influence of solution treatment temperature and yield strength on bendability

The grain boundary precipitation that affects bendability varies with solution treatment temperature. Since bendability becomes worse with increasing pre-strain, it is also considered to change with the plastic deformation capacity of the matrix. That is, bendability is expected to change with yield strength as well as solution treatment temperature.

The influence of solution treatment temperature and yield strength on the bendability were investigated by using the alloy A. The results are shown in Fig.5. Specimens were solution treated at different temperatures, aged to different yield strengths, pre-strained by 5% and bend tested through 180 degrees.



The scale for the bendability:
Good: ○ > ◔ > ◑ > ◕ > ● :Bad

Fig.5 The influence of solution treatment temperature (TST) and yield strength (YS) on the bendability of the alloy A. ([Good] means no clacks, [Bad] means a lot of large clacks)

Compared at the same yield strength level, the specimens improve in bendability with increasing solution treatment temperature. At each temperature, bendability decreases with increasing yield strength. When the solution treatment temperature is lower, bendability decreases at a lower yield strength. The bendability tends to improve with increasing solution treatment temperature and decreasing yield strength.

3.4 Influence of alloy composition on bendability

Grain boundary precipitation behavior is expected to vary in the alloy composition. Mg and Si contents and addition of Cu were investigated for their influence on the bendability. The influence of solution treatment temperature and yield strength on the bendability of the alloys A, B, and C with different Mg and Si contents and the alloy D with Cu addition are shown in Fig.6. The influence of solution treatment temperature on the grain boundary precipitation behavior of the alloys A, B and D is shown in Fig.7. The specimens were bend tested under the same conditions as described in section 3.3.

In Fig.6 (a), (b), (c), bendability tends to decrease as the amounts of Mg and Si increase, although the solution treatment temperature and the yield strength level are the same. As shown in Fig.7, when the alloys A and B are solution treated at 560℃, they do not exhibit appreciable amounts of precipitates on grain boundaries, but when the alloys are solution treated at 460℃, they have considerable amounts of precipitates formed on the grain boundaries. An alloy with larger amounts of solute Mg and Si atoms tends to contain larger amounts of precipitates on the grain boundaries.

When the alloys are solution treated at the same temperature and have approximately the same yield strength, the alloy that has fewer Mg and Si solute atoms decreases in grain boundary precipitation and improves in bendability.

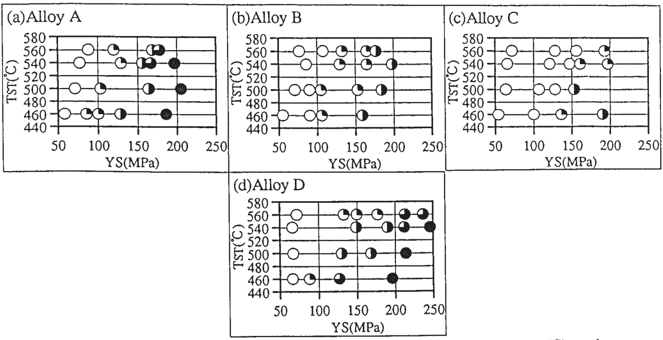


Fig.6 The influence of solution treatment temperature (TST) and yield strength (YS) on the bendability of the alloys A(a), B(b), C(c) and D(d).

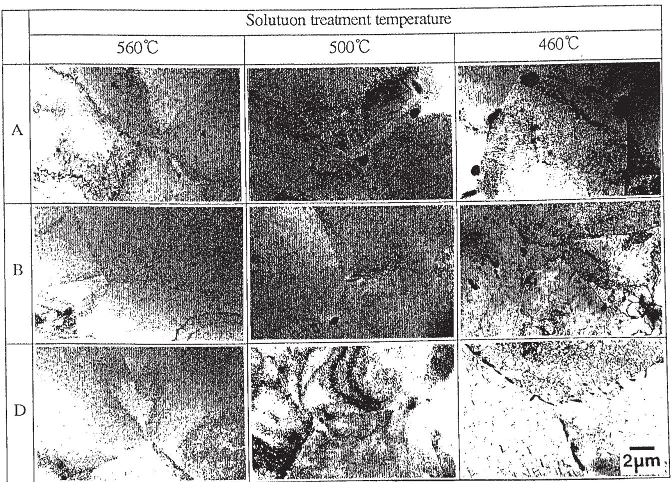


Fig.7 Bright field TEM micrographs of the alloy A, B and D solution treated at 560, 500, 460℃.

Fig.6 (b) and (d) show the influence of solution treatment temperature and yield strength on the bendability of the alloy B and D without and with Cu addition, respectively. The alloy D with Cu addition is inferior in bendability to the alloy B without Cu addition, although it is equal in solution treatment temperature and almost equal in yield strength to the alloy B.

The influence of solution treatment temperature on the grain boundary precipitation of the alloys B and D is shown in Fig.7. From Fig.7, it is clear that the alloy D with Cu addition reveals a large number of rod like precipitates on the grain boundaries in the alloy, especially when solution treated at 460℃. The EDS analysis suggests that the rod like grain boundary precipitates are Al-Cu-Mg-Si intermetallic compounds. The precipitation of the Al-Cu-Mg-Si intermetallic compounds seems to make worse the bendability of the alloy D.

As discussed above, the increased formation of precipitates on the grain boundaries is considered to be responsible for the decrease in bendability of the aluminum alloy that has high Mg and Si contents or that contains Cu, as compared with the aluminum alloy with lower Mg and Si contents or without Cu addition, if the solution treatment temperature and the yield strength being equal.

4. CONCLUSIONS

The influence of microstructure on the bendability of Al-Mg-Si alloys was investigated. The following findings were obtained:

1) The Al-Mg-Si alloys tend to decrease in bendability if they have many Mg_2Si and Si precipitates on the grain boundaries. These grain boundary precipitates are considered to promote the initiation and propagation of cracks in the bent specimens of the alloys.

2)The grain boundary precipitates seem to be formed as follows: during incomplete solution treatment or on subsequent cooling process, a complete α single phase was not obtained and over-saturated solute atoms precipitated as the Mg_2Si and Si phases on the grain boundaries. The precipitates are more likely to form on the grain boundaries when the solution treatment temperature is lower.

3)When the yield strength is practically equal, bendability of the alloys solution treated at lower temperature tends to decrease. On the other hand, if the solution treatment temperature is the same, bendability decreases with increasing yield strength.

4) To increase Mg and Si contents and to add Cu tend to promote the formation of precipitates on the grain boundaries and make worse the bendability of Al-Mg-Si alloys, if they are solution treated at the same temperature and are practically equal in yield strength.

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