TENSILE AND FATIGUE FRACTURE BEHAVIOR OF SPOT WELDED ALUMINUM SHEET ALLOYS FOR AUTO BODY APPLICATION

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ABSTRACT The influences of spot welding on mechanical properties and microstructure of Al-Mg sheet alloys for auto body application were investigated in this paper. Tensile crack propagated on the edge of the nugget and mixed rupture with dimples and intergranular fracture was shown. Fatigue fracture initiated on the edge of the nugget and propagated perpendicularly to the tensile axis and transgranular fracture with the striations was shown. The influence of loading mode on the fracture behavior of the spot welded aluminum sheet alloys was also evaluated in this study.
Keywords: *Al-Mg sheet alloys, fatigue fracture, spot welding, auto body, crack propagation*

1. INTRODUCTION

Aluminum alloys have been increasingly used in automobile industry, owing to their weight saving potential. Properties required are high strength, good formability, weldability and corrosion resistance. Al-Mg alloys have been considered as the inner panel of autobody and many new alloys with different Mg content and addition of other elements have been developed. The microstructure, mechanical properties and corrosion behavior of the alloys have been studied extensively [1-3]. Al-Mg alloys also enable high-strength welds to be obtained because the limited amount of eutectic presents in the alloys and their relatively high strength in the annealed condition. The structure of fusion welds shows the usual zones: melted zone in the center, surrounded by the heat affected zone, shading from the partially molten to the annealed zone. The strength of welds is of the order of 80~95% of the annealed strength, but ductility is not substantially reduced. The fatigue resistance of defect-free welds is only slightly lower than that of the base metals; welds containing notches, cracks, heavy segregation, porosity or inclusions are much weak[4].

At present, spot welding is still one of the most practical joint methods for aluminum alloy sheets. The influence of spot welding on microstructure and mechanical properties of the alloys has become an important research subject. The results [5,6] showed that the tensile shear fatigue strength of spot welded joints increased in proportion to the nugget diameter and the acid cleaning of the base metal was very useful as a countermeasure to prevent the degradation of mechanical property of the joints. Till now, there is no systematic investigation on the microstructure and mechanical properties of 5000 series aluminum alloy after spot welding reported.

Two Al-Mg alloys were used in this work to study the influence of spot welding on its microstructure and mechanical properties.

2. EXPERIMENTAL PROCEDURE

Two Al-Mg alloys have been used and their compositions are given in Table 1. Cold rolled sheets with the thickness of 1 mm were treated in T4 condition. The sheets in T4 condition were spot welded at the pressure of 1960 N and current of 24 kA by using a three phase AC pedestal type spot welder, and baked at 180°C for 30 minutes after spot welding.

Tensile shear specimens with the width of 30mm and length of 170mm were used for tensile and fatigue tests. Tensile shear tests were carried out using an Instron 4206 material testing machine with the crosshead speed of 2.5mm/min. Tensile shear fatigue tests were performed in an Instron 8501 fatigue testing machine at room temperature in laboratory environment at a relative humidity of about 50%. The specimens were cycled sinusoidally at 10~30 Hz, using a stress ratio of 0.1 for $1x10^7$ cycles.

Fatigue crack propagation rate was measured using the same specimens as those used for S-N curve. Center crack, single edge crack and surface crack were made in the Al-6.6Mg alloy specimens without weldment. In this test, the R value was 0.1. Fatigue crack propagation rate was also measured for spot welded specimens. The specimens were fatigue tested at R=0.1 for 990 or 1990 cycles, then tested at R=0.5 for 10 cycles. The beach marks were made in this way and b-N(crack length in the sheet thickness direction-number of fatigue cycles) data can obtained from these beach marks. After crack can be seen on the specimen surface, R value was still 0.1 and not changed anymore.

Metallographic examination and fracture analysis were made in an optical microscope, a JSM-5800 scanning electron microscope (SEM) and a JXA-8600 electron probe (EPMA). The microstructures of the alloy were also examined in a JEOL-2000 transmission electron microscope(TEM). Thin foils were prepared in a twin jet polisher with the electrolyte of 25%HNO_3 in methanol at -30°C and at a potential of 20 V.

Table 1. Chemical composition of the Al-Mg alloys. (unit: wt%)

alloy	Mg	Cu	Fe	Si	Mn	Cr	Zn	Ti	B
Al-5.5Mg	5.48	0.32	0.07	0.03	0.01	0.02			
Al-6.6Mg	6.63	0.13	0.16	0.07	0.002	0.001	0.01	0.006	0.002

3. RESULTS AND DISCUSSION

3.1 Microstructures

Microstructures of the two alloys were studied by optical microscopy, SEM and TEM. There is no much difference on the microstructures before and after baking observed by optical and SEM. Figure 1(a) and (b) show similar recrystallized structures with the equiaxed grains. The Al-5.5Mg alloy shows little coarser grains than those of the Al-6.6Mg alloy. Some inclusions can be also observed. Figure 1(c) and (d) show the TEM micrographs of the alloys after baking. The alloys contain similar microstructures with straight dislocation lines. Precipitates have not been observed in the microstructures before and after baking.

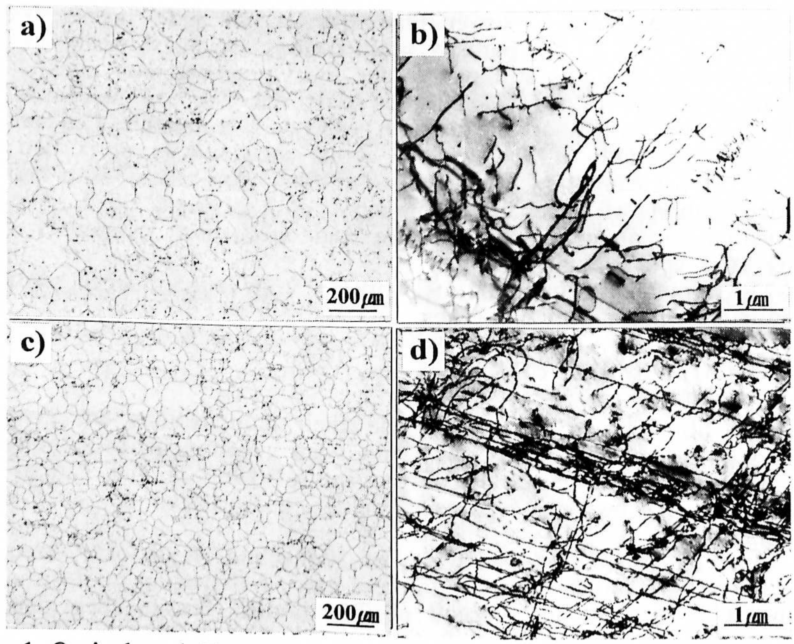

Fig. 1 Optical and TEM microstructures of Al-Mg alloys after baking.
a), b) Al-5.5Mg alloy c), d) Al-6.6Mg alloy

3.2 Mechanical properties

The tensile and fatigue properties of the two alloys without welding have been given in Table 2. The S-N curves of the two alloys are shown in Fig.2. The Al-6.6Mg alloy has higher strength and elongation compared with the Al-5.5Mg alloy. However, the fatigue strength of the Al-6.6Mg alloy is lower than that of the Al-5.5Mg alloy at $1x10^7$ cycles. Both of the alloys exhibit higher fatigue strength than their yield strengths at $1x10^7$ cycles.

Tensile shear fatigue tests were also performed for the spot welded specimens of the two alloys. The results are shown in Table 3. The Al-6.6Mg alloy shows little lower fatigue strength for the smooth specimens without welding, and higher fatigue strength for the spot welded specimens. It is well known that the fatigue property of the materials is affected by both fatigue crack initiation and propagation. In order to evaluate the fatigue property of the two alloys, it is necessary to examine the fatigue crack propagation behavior in this study.

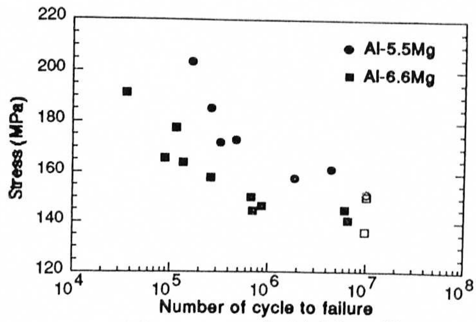

Fig. 2 S-N curves of Al-Mg alloys

Table 2. Tensile and fatigue properties of the alloys without welding.

materials & condition	tensile strength (MPa)	yield strength (MPa)	total elongation (%)	fatigue* strength (MPa)	fatigue/tensile strength
Al-5.5Mg(T4)	284	133	26.4		
Al-5.5Mg(baking)	277	130	25.2	156	0.56
Al-6.6Mg(baking)	322	149	31.2	140	0.44

* maximum fatigue stress at $1x10^7$ cycles.

Table 3.Tensile shear and fatigue properties of the spot welded alloys.

samples	nugget diameter(mm)	tensile shear load (N)	fatigue load (N)	fatigue/ tensile shear
Al-5.5Mg	6	3,594	588	0.16
Al-6.6Mg	6	4,238	637	0.16

*Maximum fatigue load at $1x10^7$ cycles; both of the alloys were tested after baking.

3.3 Fracture behavior

Figure 3 shows the tensile fracture surfaces of the two alloys. Tensile fracture surfaces of the alloys are sheared with the fracture surface parallel to the maximum shear stress direction. Tensile fractures were covered by dimples. Small amount of equiaxed dimples can be seen with shear dimples in the area.

Tension-tension fatigue fractures of the two alloys contained fatigue region and fast rupture region. Figure 4 shows overall fatigue fracture surface of the Al-5.5Mg alloy at the maximum stress of 164MPa. A large proportion of fatigue region is perpendicular to the tensile axis and striations can be seen on the surface. Most fatigue specimens show similar transgranular fracture with facets in the initiation area and striations. Facets are parallel to the maximum shear stress direction and increase with the decreasing of the applied stress. The area with striations on the surface is perpendicular to tensile axis. Fatigue fracture surfaces of the Al-6.6Mg alloy are shown in Fig.5. The fatigue fractures initiate intergranularly mainly and develop transgranularly. The corrosion product can be seen clearly on the initiation area, but there are still some intergranular parts in the propagation area and has nothing to do with the surface quality of the alloy. Hydrogen brittlement might be the reason for the formation of this intergranular fracture. For the similar fracture behavior has been reported in Al-Mg alloy[7].

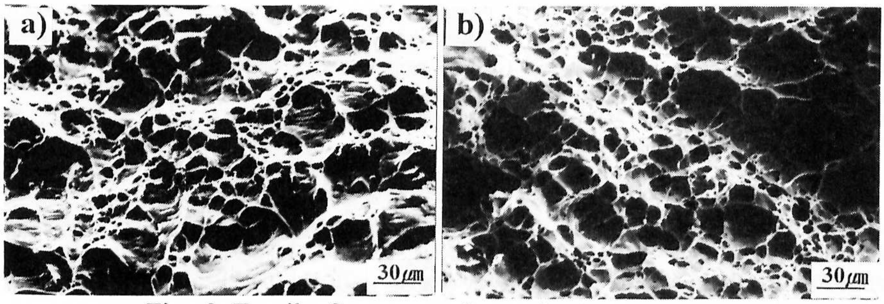

Fig. 3 Tensile fracture surface of Al-Mg alloys
a) Al-5.5Mg alloy b) Al-6.6Mg alloy

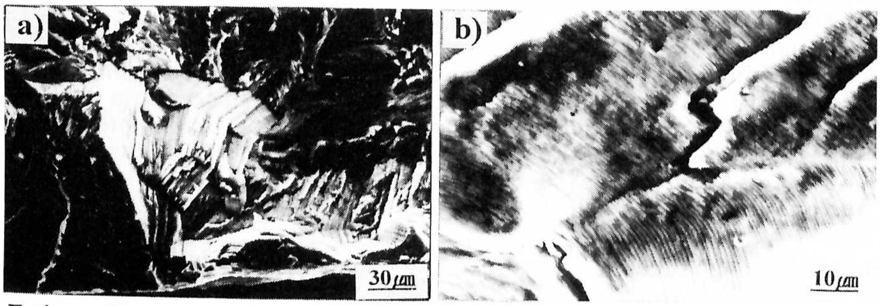

Fig. 4. Fatigue fracture surface of Al-5.5Mg alloy at the maximum stress of 164MPa, 4.35×10^6 cycles; a) crack initiation area b) striations

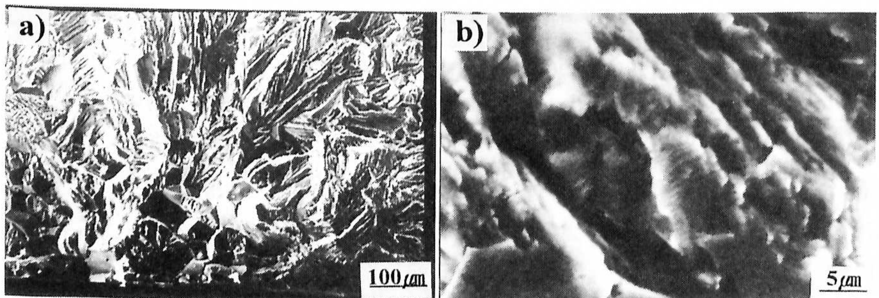

Fig. 5. Fatigue fracture surface of Al-6.6Mg alloy at the maximum stress of 141MPa, 6.51×10^6 cycles; a) crack initiation area b) striations

3.4 Fatigue crack propagation behavior

Fatigue properties were measured using the Al-6.6Mg specimens having the artificial cracks such as center crack, single edge crack and surface crack. Table 4 shows the fatigue properties of the Al-6.6Mg alloy sheet without welding.

The fatigue crack propagation behavior of the alloys is not the same in different fatigue test conditions. Figure 6(a) and (b) shows the da/dn-ΔK curve for the center crack and single edge crack of the Al-6.6Mg alloy, respectively. There is much difference in the crack growth behavior for the same alloy with different crack. However, the crack in the single edge crack specimen did not develop very stable. The two center crack specimens show nearly the same result. Fatigue crack propagation rate was also measured for spot welded specimens. The beach marks were made by changing the R values in every 1000 or 2000 cycles from 0.1 to 0.5, and b-N(crack length in the sheet thickness direction-number of fatigue cycles) data can be obtained from these beach marks. After crack can be seen on the specimen surface, R value was still 0.1 and not changed anymore.

Table 4. Fatigue properties of the Al-6.6Mg alloy sheet without welding.

specimen	crack mode	stress(MPa)*	$2a_0$(mm)	Nf(cycle)	Ni(cycle)	Ni/Nf
Vc-1	center crack	160	1.0	108,115	102,000	0.94
Vc-2	center crack	160	1.0	111,309	105,000	0.94
Vs-1	single edge crack	160	0.4**	27,953	24,132	0.86
Vf-1	surface crack	152	1.0	127,604	127,000	0.95

*Maximum fatigue stress, **a_0
Nf: Total fatigue life
Ni: Fatigue cycle at which the crack was 1mm and can be detected easily. In center crack and surface crack specimens, a_0=1.0 mm; in the single edge specimen, a_0=1.0 mm.

Table 5. Fatigue properties of the spot welded specimens

specimen	load(Kgf)*	Nf(cycle)	Ni(cycle)	Nii(cycle)	Ni/Nf	Nii/Nf
Al-5.5Mg 4#	115	98,100	59,000	76,000	0.60	0.78
Al-5.5Mg 5#	120	94,100	52,000	70,000	0.55	0.74
Al-6.6Mg 2#	100	162,000	118,000	154,000	0.73	0.95
Al-6.6Mg 3#	120	52,000	10,000	35,000	0.20	0.67

Ni: Fatigue cycle at which the fatigue crack initiated in the inner surface
Nii: Fatigue cycle at which the fatigue crack was about 1 mm and was detected on the specimen surface
*Maximum fatigue load

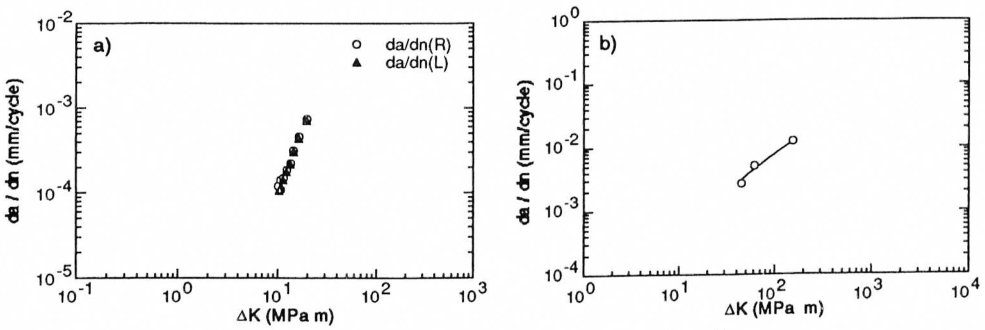

Fig. 6 da/dn-ΔK curves for Al-6.6Mg alloy
a) center crack b) single edge crack

Fatigue properties of the spot welded Al-5.5Mg and Al-6.6Mg alloys were measured. Table 5 shows the fatigue properties of the spot welded specimens used for crack growth rate measurements. The ratio of the crack initiation cycle and the total fatigue life decreases with the increasing of load. It means that the more time was spent for the specimens tested at low load. However, the Al-6.6Mg 3# specimen shows very low fatigue life compared to the Al-5.5Mg 5# specimen, which can be attributed to the low fatigue initiation cycles in the Al-6.6Mg 3# specimens. Nf-Ni=42000 cycles for the Al-5.5Mg 5# specimen whereas Nf-Ni=42000 cycles for the Al-6.6Mg 3# specimen. This result indicates that the spot welded alloys have similar propagation life at the same load.

Figure 7 shows the b-N curves for the spot welded Al-5.5Mg and Al-6.6Mg alloys. The spot welded Al-6.6Mg alloy shows the different b-N curves from the spot welded Al-5.5Mg alloy. The Al-6.6Mg alloy shows lower crack propagation rate at the early stage of the crack propagation

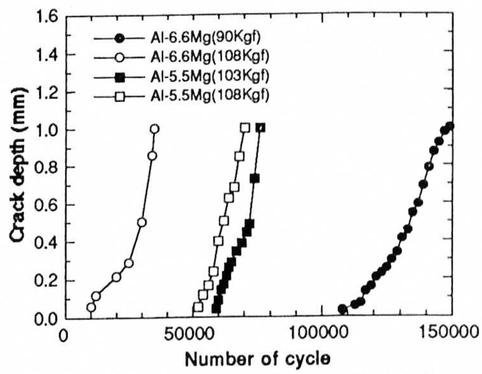

Fig. 7 Fatigue crack growth behavior of spot welded Al-Mg alloy sheet at different load amplitude.

compared with the spot welded Al-5.5Mg alloy. The a-N data were measured in the same specimens used for b-N measurement. The fatigue crack always initiates in the inner surface of the nugget edge (HAZ area) and developed to the surface of the spot welded specimens. Figure 8 shows the a-N curves of the spot welded Al-5.5Mg and Al-6.6Mg alloys. The alloys show similar crack growth behavior. The main crack propagated to about 5 mm, and then propagated slower for several thousand cycles. At the same time, two cracks initiated and propagated near the tip of the main crack. Finally those cracks connected with the main crack and the crack propagated at high speed. Compared the data in Table 4 and Table 5, the spot welded specimens have lower Ni/Nf value. Those results indicate that the spot welded specimens have the similar fatigue behavior as the pre-cracked specimens.

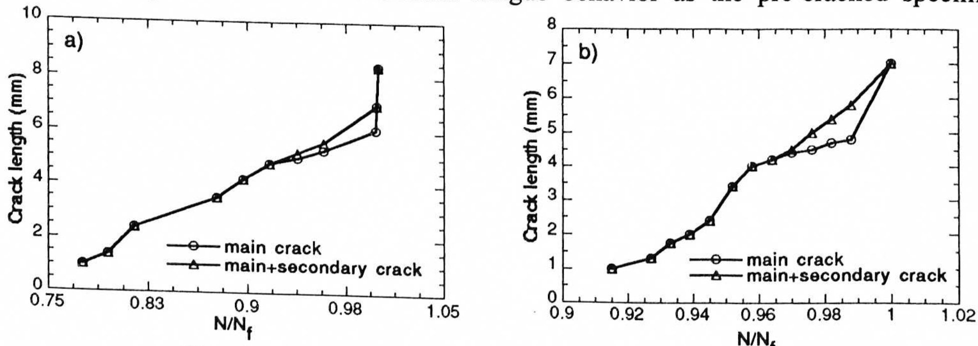

Fig. 8 a-N curves for the spot welded Al-Mg sheets
a) Al-5.5Mg b) Al-6.6Mg

CONCLUSIONS

1. The increase in Mg content can increase the ultimate strength and yield strength with the ductility. The Al-6.6Mg alloy shows very good combination of strength and ductility.
2. The Al-6.6Mg alloy shows lower fatigue strength compared to that of the Al-5.5Mg alloy.
3. The alloys show similar tensile fracture with dimples. The intergranular fatigue fracture can be seen in the initiation area and propagation area near initiation area for the Al-6.6Mg alloy. The intergranular fracture in the initiation area is affected by corrosion on the surface of the sheet. The intergranular fracture in the propagation area might be affected by hydrogen. The Al-5.5Mg alloy shows typical fatigue fracture in aluminum alloys.
4. Fatigue properties of the spot welded Al-5.5Mg and Al-6.6Mg alloys show that the ratio of the crack initiation cycle and the total fatigue life decreases with the increasing of load. It means that more time was spent for the specimens tested at low load.

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