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Shueiwan H. Juang

Department of Mechanical and Mechatronic Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C., shjuang@mail.ntou.edu.tw

Shyh-Ming Wu

Costco #690, U.S.A.

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STUDY ON MECHANICAL PROPERTIES OF A356 ALLOYS ENHANCED WITH PREFORMED THIXOTROPIC STRUCTURE

Shueiwan H. Juang* and Shyh-Ming Wu**

Key words: A356 alloy, thixotropic structure, mechanical properties.

ABSTRACT

A preformed A356 alloys with thixotropic structure (designated SSM-A356) was systematically studied on mechanical properties in order to establish the database for further investigations in forming and heat treatment. Because of the specific microstructure and characteristics, the heat treatment conditions of SSM-A356 were explored through the observations of microstructure and the measurement of micro-hardness. In the investigation of heat treatment, it was observed that the eutectic silicon was refined and spheroidized which is unlikely for conventional processing. The mechanical testing results showed that the yield and ultimate tensile strength of SSM-A356 were respectively around 115% and 34% greater than those of conventional A356, and the elongation was also 2-3 times larger. According to the analysis of fracture mode via fatigue test, the crack propagation was in the way of trans-granular which is a typical type of ductile fracture. Thus, an excellent ductility for SSM-A356 was expected. From the experimental analysis results, it could be concluded that the superior mechanical behaviors of SSM-A356 are basically attributed to the refinement of microstructure and the spheroidization of eutectic silicon. This structure can be maintained during forming by further processing of die or squeeze casting.

I. INTRODUCTION

Metals were processed at either solid or molten state in traditional metal forming processes. The major near-net-shape forming process at molten state is die casting, which has the advantages of high productivity and dimensional accuracy. However, porosity is commonly found in die cast parts, thus applications are limited. Semi-solid forming processes provide a practical way to overcome the problems of porosity.

In a hot-tearing experiment, Flemings *et al.* found out that a

slurry with near spherical primary crystals suspending in the liquid metal matrix would form in a partially-solidified metallic alloy if continuous shearing was applied [5]. The material can have a good fluidity when the solid fraction is as high as 60%. Thus the metallic alloy can be formed into a shape at partially-solidified state.

When a heat-treatable A356 aluminum alloy undergoes precipitation hardening (age-hardening), fine precipitants will dissolve completely in saturated matrix to achieve high strength in material [2]. The processing temperature should be kept close to the eutectic temperature of the alloy in order to obtain maximum amount of solid solution [4], while the processing time should be long enough to allow all solute atoms to dissolve into the matrix. The solid solution should then be quenched at a high cooling rate to reach a low temperature and obtain a super-saturated solid solution. The quench interval should be short in order to prevent deterioration in material mechanical properties such as tensile strength, yield strength and elongation [2, 3]. It is suggested in the ASTM standard that the water quench has to be finished in 10 seconds to obtain uniform Mg_2Si precipitation and better mechanical characteristics. When the super-saturated solid solution undergoes aging treatment, a large amount of small and uniformly-distributed precipitants will appear thus the mechanical properties of the material can be improved. Uniform and delicate Mg_2Si precipitants can be obtained in the matrix of a heat-treatable Al-Si-Mg casting part with T6 treatment, leading to improvements in its tensile strength, elongation and toughness [7, 8].

A preformed A356 aluminum alloy with thixotropic structure (designated SSM-A356) was used in this study. Two sets of ASTM standard specimens were first prepared, of which one set was T6 treated with processing conditions proposed by Wu [9]. Tensile, impact and fatigue tests were performed on the T6-treated and non-treated specimens and the results were compared.

II. TEST EQUIPMENT AND METHODS

Raw materials used in this study were obtained from an SSM-MHD caster in Europe. Two sets of ASTM specimens were prepared. One set underwent a solid solution treatment at 540 °C for 12 hours, water quench, and then an aging treatment at 155 °C in air for 12~19 hours. Another set was as-cast without

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*Department of Mechanical and Mechatronic Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.

** Costco #690, U.S.A.

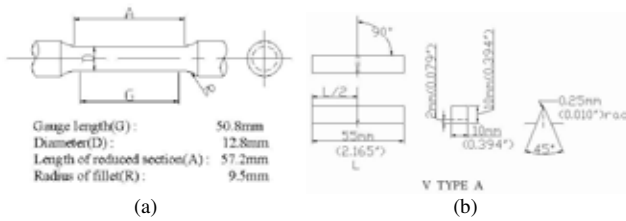


Fig. 1. Test specimens of SSM-A356: (a) tensile test, (b) impact and fatigue tests.

any treatment. The two sets of specimens were used for tensile, impact and fatigue testing as follows:

1. Tensile Test

Standard test bars shown in Fig. 1(a) were machined following ASTM B557-94 standard [1], with a length of 155~160 mm. Diameters at two ends and center portion are 18 mm and 12.8 mm, respectively. Experiments were done using a Zwick-1475 material testing machine. Specimens were held at two ends by automatic hydraulic clamps, and the test conditions were input from a computer. Cross-head speed was 1 mm/min, and the gage length was set to 50.8 mm.

2. Impact Test

Specimen dimensions were 10×10×55 mm with a V-shape notch, shown in Fig. 1(b), based upon ASTM E8-96 standard [1]. Tests were performed using a CHARPY-TINIUS OLSEN 64 impact testing machine with impact energy of swinging pendulum 358 Joule, impact speed 5.12 m/s and testing temperature 20 °C.

3. Fatigue Test

Dimensions of specimens prepared according to ASTM E812-91 standard [1] were the same as in impact tests. An MTS-810.15 fatigue testing machine was used to perform the 3-point bending tests with a 40-mm span at the bottom. The maximum loading F_{max} was 1.2~2.5 kN, radius 0.1R, frequency 3 Hz, and loading frequency 7000~25000 cycles.

III. RESULTS AND DISCUSSIONS

The results obtained from the two sets of SSM-A356 specimens conducting on the tensile, impact and fatigue tests under the same conditions were discussed as follows.

1. Tensile Test

The tensile properties of SSM-A356 under different states are given in Table 1. The yield strength of as-cast SSM-A356 was only 128 MPa, which is a little lower than that of conventional alloys, but the tensile strength 254 MPa was close to that of conventional one. It was noted that the elongation of as-cast SSM-A356 was 13.3%, which is about 2~3 times of the conventional alloys. After applying the T6 treatment, solid solution treatment at 540 °C for 12 hours and aging treatment at 155 °C for 12 hours, the elongation of SSM-A356 was reduced to 11.5%, however, the yield and tensile strength were dramati-

Table 1. Comparison of strength and elongation under different states for SSM-A356 (T6 treatment: solution treatment 540 °C /12 hrs and aging temperature 155 °C).

State of specimen	Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)
ASTM specs value*	165~185	228~262	3.5~5.0
As-cast	128	254	13.3
T6 treatment (aging 12 hr)	276	341	11.5
T6 treatment (aging 19 hr)	280	343	10.8

Note: *A356 without thixotropic structure after T6 treatment.

cally increased to 276 MPa and 341 MPa, respectively. That is, there is an improvement about 115% and 34% on yield and tensile strength, respectively, although having a 14% reduction on elongation. It also indicated that the changes in mechanical properties were limited as the aging duration was changed from 12 hours to 19 hours.

The improvement on mechanical behaviors of SSM-A356 was basically attributed to the factors such as:

- Reduction of macro-defects. The hydrogen dissolution into aluminum alloys is increased significantly in a liquid state, and leads to a large amount of gas porosity during solidification stage. However, SSM-A356 is formed and solidified in a semi-solid state. The hydrogen dissolution is relatively decreased, leading to less gas porosity. Moreover, the shrinkage porosity is also reduced due to lower forming temperatures.
- Spheroidization of eutectic silicon. The spheroidization of eutectic silicon in SSM-A356 is via solid diffusion, which is driving in virtue of the difference of silicon composition in the liquid state and in the solid solution. During the phase transformation, eutectic silicon is refined and almost completely spheroidized. This causes that the crack was not propagating along the sharp interface of eutectic silicon and matrix. Therefore, SSM-A356 revealed better strength and elongation.
- Refinement of microstructure. The microstructure of SSM-A356 was refined via a specific process, either mechanical stirring or MHD. The lattice space was about 10 μm, which is much smaller than that of material without thixotropic structure. In addition, the distribution of eutectic silicon was uniform with a particle size around 3~5 μm. Material with particle dispersion strengthening effect would be improved on strength significantly.

2. Impact Test

The toughness of SSM-A356 is listed in Table 2. The impact value of as-cast SSM-A356 was 11.5 Joule, which is much higher than that of conventional A356 with T6 treatment, having 3.8 Joule only. After applying T6 treatment to as-cast SSM-A356, the impact value was dropped to 4 Joule, which is close to that of conventional alloys. As compared to the elongation with a slight reduction before and after T6 treatment, this

Table 2. Comparison of impact value under different states for SSM-A356 (T6 treatment: solution treatment 540 °C /12 hr and aging temperature 155 °C).

State of specimen	Impact value (Joule)
ASTM spec value*	3.8
As-cast	11.5
T6 treatment (aging 19 hr)	4.0

Note: *A356 without thixotropic structure after T6 treatment.

Table 3. Comparison of crack propagation under different states for SSM-A356 (Radius: 0.1R, frequency: 3Hz).

Specimen No.	State of specimen	Maximum load (kN)	Load cycles	Crack length (mm)
1	As-cast	2.5	7,000	2.0
		2.5	300	-
2	As-cast	1.5	7,000	1.5
		1.5	1,300	2.0
		1.2	5,300	2.5
3	T6 treatment*	2.5	22,500	1.0
		2.0	3,000	2.5

Note: *Solution condition: 540 °C /12 hr and aging condition: 155 °C /19 hr.

obvious drop on toughness of SSM-A356 after T6 treatment might be related to strain rate under the test and fracture mechanism of almost completely spheroidized eutectic silicon. Further study on improvement of toughness is required to be conducted for reaching an optimum treatment conditions upon material strength and toughness.

3. Fatigue Test

A series of fatigue tests, using impact test specimens, was conducted to investigate the fracture mechanism of SSM-A356 under different loads. In the test a natural crack was initialized on the specimens, then following a fatigue test. If the specimen was not broken off, an optical electron microscope (OEM) was utilized to observe and measure the crack propagation with different multiplication factors. The observed results are showed in Table 3.

Table 3 indicated that Specimen 1 was as-cast SSM-A356 under a fatigue load of 2.5 kN. A natural crack was appeared with 2.0 mm in length as the fatigue frequency at 7,000 cycles. If the test was continued under the same load, the test specimen was broken off at 300 cycles more. Crack propagation could not be observed from this test.

Specimen 2 in Table 3 was also as-cast SSM-A356 under an initial fatigue load 1.5 kN. A natural crack appeared with 1.5 mm in length as the fatigue frequency at 7,000 cycles. The crack length propagated to 2.0 mm as the test was continued 1,300 cycles more under the same load. Then, the test was continued 5,300 cycles added under a new load 1.2 kN, leading the crack with 2.5 mm in length. Fig. 2 showed the crack propagation of Specimen 2 under the combination load. It was evident that there were two segments with different width in the crack, shown in Fig. 2(a). The wide one was formed via the load 1.5 kN and the narrow one via 1.2 kN. Fig. 2(b) showed that the crack propagation was in the way of trans-granular, rather than along

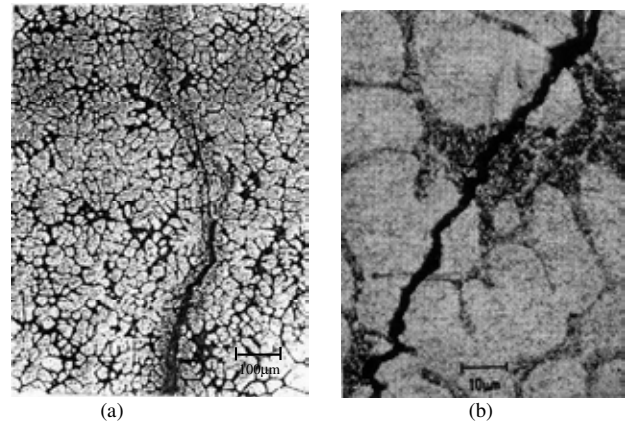


Fig. 2. Crack propagation of as-cast SSM-A356 under initial load 1.5 kN and 1.2 kN followed, (a) x100 and (b) x1000.

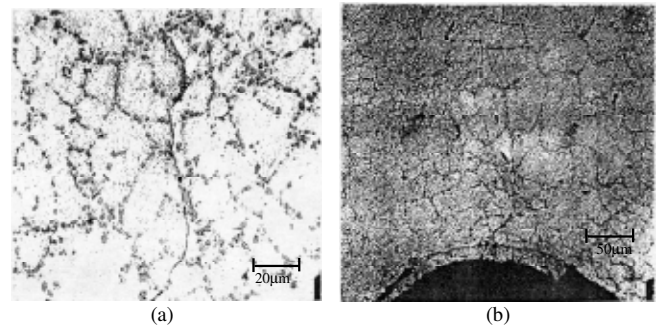


Fig. 3. Crack propagation of SSM-A356 with T6 treatment, (a) fatigue load 2.5 kN (x500) and (b) fatigue loads 2.5 kN and then 2.0 kN (x200).

the grain boundary. This type of fracture mode led SSM-A356 with superior elongation and strength.

Specimen 3 in Table 3 was T6 treated SSM-A356, solid solution treatment at 540 °C for 12 hours and aging treatment at 155 °C for 12 hours, which showed a significant raise on the fatigue property. A natural crack with 1.0 mm in length only appeared as the fatigue frequency at 22,500 cycles under a fatigue load 2.5 kN. The crack propagation also revealed the typical type of trans-granular fracture, shown in Fig. 3(a). Following the test with a fatigue load 2.0 kN, Fig. 3(b) showed that the crack propagation in accordance with the trans-granular fracture mode was more evident as 30,000 cycles more applied.

IV. CONCLUSIONS

Raw materials used in this study were SSM-A356, which were categorized into two sets of ASTM specimens. One set underwent a T6 treatment, solid solution treatment at 540 °C for 12 hours and aging treatment at 155 °C for 12 hours, and another set was as-cast without any treatment. Two sets of specimens were investigated under the same conditions for tensile, impact and fatigue testing. The significant results were outlined as follows:

1. It explored that both yield strength and ultimate tensile strength were substantially increased for T6 treated SSM-A356. The measured yield strength and ultimate ten-

sile strength were respectively about 115% and 34% greater than those of conventional alloys. It was also observed that the elongation was 2~3 times larger than the ASTM specified data, also leading to improvements on the relative fatigue properties.

2. It showed that the improvement on the mechanical properties of SSM-A356 was correlated to the reduction of gas and shrinkage porosity, refinement of microstructure, and spheroidization of eutectic silicon. This result was same as that addressed by Saigal [6]. That is, the mechanical properties were affected by the shape and distribution of silicon inside the aluminum matrix. In general, a uniform distribution of silicon with refinement and spheroidization would go towards to improvement on elongation, impact and fatigue due to lower interface energy. For SSM-A356, it had a fine thixotropic structure during the preparation of raw material and its following processing. The improvement on the impact and fatigue properties as compared to conventional A356 would be expected.
3. According to the analysis of fracture mode via fatigue test, it can be concluded that the crack propagation was in the way of trans-granular, which is a typical type of ductile fracture, rather than along the boundary between eutectic silicon and matrix. This phenomenon was observed for SSM-A356 with either T6 treatment or not.

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