Crack Propagation Behavior of A356 and Al-1Si-0.3Mg Aluminum Alloys under Resonant Vibration

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By using the A356 aluminum alloy (Al-7Si-0.3Mg) with dispersed eutectic silicon particles and the single-phase Al-1Si-0.3Mg alloy, this study was carried out to investigate how eutectic silicon influences the crack propagation behavior under resonant vibrations in natural and overaging conditions. In the natural aging condition, the cracking modes of these two alloys resemble each other and the cracks through slip bands occur. Besides slip band cracking, as the cracks in the A356 alloy pass through the interdendritic zones with eutectic silicon clustering, they propagate through broken silicon particles or silicon particle/matrix interfaces. So, the resistance to crack growth of the Al-1Si-0.3Mg alloy is slightly higher than A356 alloy. For the overaging condition, the crack paths of these two alloys obviously differ from each other. The cracking mode of the Al-1Si-0.3Mg alloy largely displays the striation feature. However, owing to the existence of brittle silicon particles, the cracking exhibits a preferred direction towards the silicon particles and runs through broken silicon particles or silicon particle/matrix interfaces. Thus, the cracking resistance of A356 alloy is significantly lower than Al-1Si-0.3Mg alloy. Moreover, the crack growth resistance of the Al-1Si-0.3Mg alloy in the natural aging condition is slightly higher than that under the overaging condition. In contrast, for the A356 alloy, the former shows much higher resistance than the latter.

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I. Introduction

Vibration problems frequently occur in daily life, such as in machines, construction and traffic. Among these problems, resonant vibration is the most likely scenario for failure to occur. Therefore, the fracture features of materials under resonant vibration must be thoroughly explored. In lieu of increasing concerns over energy conservation, aluminum alloys have been extensively used to reduce the weight of motorcycles or automobiles. Of these applications, Al-Si-Mg cast aluminum alloys have been extensively used in structural components, e.g. frames and turners, owing to their excellent castability, mechanical properties and corrosion resistance\(^{(1)}\). In practice, the resonant vibration that may incur failure in these components still persists under abnormal circumstances. Therefore, in this study, we investigated the crack propagation behavior of Al-Si-Mg alloys using a vibration test machine capable of generating the resonant condition.

According to the previous study\(^{(2)}\), the second-phase eutectic silicon particles of the A356 alloy heavily influence the crack propagation behavior. Thus, the Al-1Si-0.3Mg alloy, was selected as the test material since its matrix possesses properties similar to A356 alloy and contains no eutectic silicon. By doing so, the extent to which eutectic silicon influences the cracking mode can be fully realized. On the other hand, the previous study demonstrated that the crack propagation trajectories of the solution-treated alloys (natural aging) differ from those of as-cast alloys\(^{(2)}\). This discrepancy may be attributed to the coherent precipitates of the solution-treated alloys. Therefore, in addition to natural aging, the overaging alloys with incoherent precipitates were investigated to further understand how eutectic silicon influences the crack propagation behavior under resonant vibration.

II. Experimental Procedures

A356 and Al-1Si-0.3Mg alloys were prepared by melting pure aluminum, magnesium and silicon using a high frequency induction furnace. After degassing, the A356 and Al-1Si-0.3Mg melts were poured into a Y-shaped permanent steel mold with a parallel section of 40 mm × 100 mm × 100 mm at 680°C and 720°C, respectively. Table 1 lists the chemical compositions of these two alloys. The alloys were solutionized at 535°C for 10 h then quenched in water. The aging treatments in this study included natural aging (NA) at room temperature for 7 d and overaging (OA) at 200°C for 10 h, respectively.

Figure 1(a) schematically depicts the vibration setup used herein. Figure 1(b) illustrates the test specimens’ shape and dimensions. According to this figure, each test specimen was clamped on a vibration shaker and the deflection sensor on the specimen’s end measured the specimen’s deflection. Prior to testing, the frequency of the vibration shaker was varied to determine the
This study also attempted to realize the characteristics of crack propagation by measuring the crack path tortuosity represented by the ratio of main crack length and projected crack length along notch directions. In addition, the influence of eutectic silicon in current study was investigated by measuring the line intercepted density (LID) and the crack intercepted density (CID) of eutectic silicon of the A356 alloy to investigate the influence of eutectic silicon in the present study. The definition of LID denotes the number of eutectic silicon particles per unit length and CID represents the number of eutectic silicon particles intercepted by crack per unit crack length along the notch direction.

III. Results

1. Microstructure and microhardness data

Figure 3(a) illustrates the microstructure of the Al-1Si-0.3Mg alloy. According to this figure, the Al-1Si-0.3Mg alloy is a single-phase material and the silicon is nearly in solid solution. For the A356 alloy, owing to that the morphology of eutectic silicon and grain structure does not change under different aging treatments, the microstructures of the OA specimen are illustrated in Figs. 3(b) and (c). After solution treatment at 530°C for 10 h, the silicon particles of the A356 alloy are obviously spheroidized. Table 2 summarizes the microhardness data on the A356 and Al-1Si-0.3Mg alloys. According to this table, the microhardness values of these two alloys closely resemble each other under either the NA or OA condition.

2. Deflection of the specimens

Figure 4 reveals the specimens’ deflection as a function of vibration cycle. All specimens exhibit a similar trend in the variation of the deflection, which can be classified into three stages throughout the test. In stage I, the
deflection increases with the number of vibration cycles. In our previous study\(^2\), the specimen's hardness also increases with vibration cycles during this stage, namely possessing the feature of work hardening. This feature causes a higher effective elastic modulus and poorer damping capacity. Thus, the deflection of specimen rises. The deflection then maintained about constant during stage II. In this stage, the cracks propagate principally. As the cracks were sufficiently long, both the effective elastic modulus and resonant frequency of the specimen
Fig. 6 Crack length vs. vibration cycle for the specimens at: (a) natural-aged condition; (b) overaged condition.

3. Crack propagation behavior

Figures 5(a) and (b) depict the variation in crack length of all specimens with the vibration cycle. According to these figures, the crack growth rate of the NA specimen of the Al–1Si–0.3Mg alloy is slightly higher than the OA specimen. However, for the A356 alloy, the crack growth rate of the NA specimen is distinctly higher than the OA specimen. Figures 6(a) and (b) compare the difference between these two alloys under the same aging condition. At the NA condition, the crack growth rate of the Al–1Si–0.3Mg alloy is close to that of the A356 alloy. In contrast, the OA specimen of the Al–1Si–0.3Mg alloy possesses considerably higher resistance to crack propagation than the A356 alloy.

A close examination of the crack profiles in Figs. 7(a) and (b) reveals the special feature in which cracks extend through slip bands; these bands appear on two alloys in the NA condition. For the A356 alloy, in addition to the above feature, the cracks also run through broken silicon particles or particle/matrix interfaces in the interdendritic zones with silicon particle clustering, as shown in Fig. 7(c). On the other hand, observing the fracture surfaces by SEM (Figs. 8(a) and (b)), the NA specimens of the two alloys possess the characteristics of crystal planes on the fracture surfaces. Between these two alloys, the feature of crystal planes is more evident owing to the disappearance of eutectic silicon in the Al–1Si–0.3Mg alloy. To ensure the orientation of crystal planes, the fracture surfaces were etched by the etchant of \(50\text{H}_2\text{O}:50\text{HNO}_3:32\text{HCl}:2\text{HF}\). According to our results,
triangular etch pits emerge on the crystal planes on the fracture surfaces of the two NA specimens, as shown in Figs. 8(c) and (d). From the morphology of the pits, the orientation of crystal planes can be verified to be close to \{111\}, i.e. the slip planes.

For the OA condition, the cracking mode in Figs. 9(a) and (b) differs from that in the NA condition. Moreover, the cracks along slip bands no longer appear on the propagation paths. Between the two alloys, silicon particles obviously influence the paths of the A356 alloy and show some preferred trend toward the zone of eutectic silicon clustering. (Fig. 9(b)) Figures 10(a) and (b) reveal the crack propagation process of the OA specimen of the A356 alloy under different vibration cycles. According to these figures, the stress of a crack tip can cause the microcracks to form at silicon particles or microvoids at the eutectic silicon/matrix interfaces. As resonant vibration proceeds, the microcracks or microvoids link to the main crack, then the crack extends forward. Figure 10(c) shows the SEM photography with a higher magnification of the crack profile. This figure reveals that the crack extends through the broken silicon particles or the silicon particle/matrix interfaces. Figures 11(a) and (b) display the SEM photographs of the fracture surfaces of the OA specimens. According to these figures, the fracture surfaces of the two alloys possess different features. For the Al-1Si-0.3Mg alloy, the fracture surface shows a primarily striation feature. However, the fact that the A356 alloy possesses eutectic silicon accounts for why the striation is inhibited and the roughness increases.
IV. Discussion

According to the results of this study, the crack propagation modes for the NA and OA conditions distinctly differ from each other. In the NA condition, the cracks of the two alloys occur mainly through slip bands. Zhen et al. have reported that in the tensile deformation of Al-Mg-Si alloys whose precipitate/matrix interfaces are coherent, the slip motion of dislocations can shear the precipitates and subsequently causes the stress for dislocation slip to decrease. In such a condition, dislocations slip preferentially on these slip planes, in which dislocations have already existed. Therefore, the dislocation motions are confined within narrow bands, namely inhomogeneous deformation. With respect to crack propagation, this phenomenon can result in cracks to extend through slip bands. In this study, the slip band cracking was observed on both of these alloys in the NA condition owing to the coherent interfaces between precipitates and the matrix. Moreover, the appearance of {111} crystal planes on the fracture surfaces can also accounts for this phenomenon. In the OA condition, the precipitates are incoherent with the matrix, so they are looped and bypassed by dislocations as the deformation occurs. Thus, in this study, the cracks through slip bands disappear.

The previous investigations involving fatigue crack growth have revealed that the tortuous crack and crack closure can reduce the driving force for crack propagation. Between these two factors, the closure effect plays a predominant role in reducing the crack growth rate. In this study, the NA specimens of the Al-1Si-0.3Mg alloy exhibits the character of slip band cracking and the crack path tortuosity is as high as 1.41 (Table 3). However, the loading condition in the current test belongs to bending and the crack depth confines within the surface of specimen. Therefore, the influence of the crack closure decreases. For this reason, the resistance to crack growth of the NA specimens of the Al-1Si-0.3Mg alloy is slightly higher than the OA specimens. On the
Table 3  Crack path tortuosity.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Natural aging</th>
<th>Over aging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-1Si-0.3Mg</td>
<td>1.41</td>
<td>1.13</td>
</tr>
<tr>
<td>A356</td>
<td>1.23</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Table 4  Density of line intercepted (LID) and crack intercepted (CID) silicon particles of A356 alloy. (No. /mm)

<table>
<thead>
<tr>
<th>Condition</th>
<th>LID</th>
<th>CID</th>
<th>CID/LID</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural aging</td>
<td>25</td>
<td>25</td>
<td>1.00</td>
</tr>
<tr>
<td>Over aging</td>
<td>24</td>
<td>33</td>
<td>1.38</td>
</tr>
</tbody>
</table>

other hand, for the A356 alloy, the crack paths of the NA specimens are also mainly through slip bands. However, in the OA condition, their growth rates are enhanced by the brittle second-phase eutectic silicon. Thus, the OA specimens possess a substantially higher crack propagation rate than the NA specimens.

In the NA condition, most of the crack propagation paths of the A356 alloy resemble those of the Al-1Si-0.3Mg alloy. Furthermore, compared to the A356 alloy, the fact that the Al-1Si-0.3Mg alloy is a single-phase material accounts for why the phenomenon of slip band cracking is more evident and crack paths are more meandering. However, the volume fraction of eutectic silicon is only 9% and its particles are mostly concentrated at the interdendritic zone. Therefore, the cracking mode of the A356 alloy can be divided into two regions. Inside the dendrite, the cracks extend through slip bands and are through broken silicon particles or eutectic silicon/matrix interfaces at the interdendritic zone. In sum, under the NA condition, the resistance to crack propagation of the Al-1Si-0.3Mg alloy is slightly higher than A356 alloy.

With respect to the OA condition for the Al-1Si-0.3Mg alloy, the disappearance of eutectic silicon makes the fracture process blunting and resharpens of the cracks. Thus, the fracture surfaces of the OA specimen display a striation feature. For the A356 alloy, the silicon particles inhibit the striation and therefore the possibility of its appearance decreases. In such a condition, the silicon particles affect the crack propagation behavior. In addition, according to Table 4 in which the OA specimens show the higher CID/LID ratio, we can conclude that the cracks move preferably towards the interdendritic zone with eutectic silicon clustering. Moreover, the fact that eutectic silicon is the brittle second phase accounts for why the OA specimens of the A356 alloy possess significantly lower resistance to crack growth than the Al-1Si-0.3Mg alloy.

(1) Cracks through the slip bands are observed on the NA specimens of two kinds of Al alloys. Between these two alloys, the cracks of the Al-1Si-0.3Mg alloy fully extend through the slip bands. For the A356 alloy, inside the dendrite, the cracks are also through the slip bands. However, the cracks go through broken silicon particles or eutectic silicon/matrix interfaces while passing through the interdendritic zone with eutectic silicon clustering.

(2) The cracking modes of two alloys at OA condition obviously differ from each other. For the Al-1Si-0.3Mg alloy, the mode displays the striation feature. For the A356 alloy, owing to the influence of brittle silicon particles, the cracks go preferably towards the interdendritic zone with eutectic silicon clustering. While crossing this zone, the cracks extend through broken silicon particles or eutectic silicon/matrix interfaces.

(3) In the NA condition, the Al-1Si-0.3Mg alloy possesses a little higher resistance to crack growth than the A356 alloy. However, in the OA condition, the resistance of the former is much higher than the latter.

(4) For the Al-1Si-0.3Mg alloy, the crack path tortuosity of the NA specimen is high. On the other hand, the influence of crack closure is negligible because the crack depth is not through the specimen thickness. In sum, the resistance to crack growth of the NA specimen is slightly higher than the OA specimen. For the A356 alloy, the cracks of the OA specimens display a preferred trend toward the interdendritic zone with eutectic silicon. Therefore, their resistance to crack propagation is lower than that of the NA specimens.

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REFERENCES


V. Conclusion

Based on the results of this study, we can conclude the following: