Effect of Post Weld Heat Treatment on Microstructures and Mechanical Properties of AZ31B Friction Welded Joint

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AZ31 magnesium alloy was welded by friction welding and the effect of post weld heat treatment on microstructures and mechanical properties were investigated. Fine grained microstructure whose minimum grain size is approximately 1 μm was formed at the weld interface by dynamic recrystallization due to hot-heavy working. Although abnormal grain growth which is often found in stir zone in friction stir welding occurred near weld interface where the material was work hardened, the area was limited and did not affect the mechanical properties of weld interface. The tensile and fatigue strength of as weld joints were equal to those of base metal and did not decrease until grain size increased to approximately 15 μm. The decrease in the Hall-Petch slope was found when the grain size decreased less than 3 μm in grain size in terms of yield stress. [doi:10.2320/matertrans.48.44]

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1. Introduction

Magnesium alloys are attractive for automotive industry due to their high specific strength. Reliable joining technique is needed to build up structures with magnesium alloys. However, since magnesium is one of the most active metals, conventional fusion welding process such as GTAW often results in defect and require severe controlled atmosphere. Recently, friction stir welding (FSW) which is believed to be operated in solid state achieves a successful outcome on joining of aluminum or magnesium alloys.¹⁻³ One of the specific microstructural features on friction stir zone is grain refinement³,⁴ which is caused by hot-heavy-working in solid state, resulting in additional valuable mechanical properties in some cases. On the other hand, the fine grained microstructure of stir zone is unstable at elevated temperature in comparison with normal microstructure. It has been reported abnormal grain growth occurred in the stir zone of friction stir welded aluminum alloys.⁵,⁶

Friction welding is a more classic process than FSW in terms of use of friction phenomenon. Therefore, many researches have been published on mechanical properties,⁷,⁸ microstructures,⁹,¹⁰ modeling,¹¹ welding temperature estimation¹²,¹³ and so on in wide variety of materials from steels to ceramics. However, lack of published works on effect of post weld heat treatment (PWHT) will be a serious problem in near future. This is because the feature of microstructure of friction welding is also grain refinement that is caused by similar mechanism to FSW, that is, dynamic recrystallization.⁹,¹⁰ However, the grain growth behavior of friction weld joint has not been studied yet. So it is necessary to investigate thermal stability of microstructures made by friction welding.

Moreover, it is well known that formability of magnesium is poor because of its hcp crystal structure. One of the solutions must be a grain refinement. In terms of the effect of grain size on mechanical properties of magnesium alloys, some different results were reported. Park et al. found classical Hall-Petch relation about hardness in friction stir welded magnesium alloy.¹¹ On the other hand, Wilson reported 0.1% proof stress of pure magnesium decreased with decreasing grain size after reaching peak value.¹⁴ Since fine grained microstructure is also obtained by friction welding,⁹,¹⁰ magnesium alloys with wide variety of grain size would be produced by PWHT.

In the present study, the effect of PWHT on microstructures and mechanical properties of friction welded magnesium alloy is investigated. Beside, the relation between grain size and mechanical properties of magnesium alloy is also described.

2. Experimental Procedures

The material used in the present study was hot extruded AZ31B magnesium alloy bar whose diameter was 19 mm. The material was worked for the welding as shown in Fig. 1 and the faying surface was cleaned with acetone prior to the welding. The chemical composition is shown in Table 1. The optimum welding condition, 70 MPa of friction

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Table 1 Chemical compositions of AZ31B (mass%).

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Zn</th>
<th>Mn</th>
<th>Fe</th>
<th>Si</th>
<th>Ni</th>
<th>Cu</th>
<th>Mg</th>
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<tr>
<td></td>
<td>3.17</td>
<td>0.88</td>
<td>0.26</td>
<td>0.0010</td>
<td>0.0008</td>
<td>0.0040</td>
<td>0.0200</td>
<td>Bal.</td>
</tr>
</tbody>
</table>
Fig. 2 Geometry of specimens for tensile test (a), and fatigue test (b). (unit: mm).

Micro-Vickers hardness distribution along the rotational axis near the weld interface is shown in Fig. 4 and mean grain size at each position is shown in the plot. Hardness near the weld interface is larger than that of base metal. The peak value of hardness is found at the work hardened region where is located approximately 3 to 6 mm away from the weld interface. The additional hardness is caused by either grain refinement or work hardening. Since in the case of friction welding, recrystallized fine grains at the weld interface contain few dislocations,9,10) the additional hardness at the weld interface is due to the grain refinement. On the other hand, grain size at the work hardened region is similar to the base metal. So the additional hardness there is caused by work hardening.

3.2 Microstructural development by PWHT

Figure 5 shows the microstructures at the weld interface before and after heat treatment at 573 K. Abnormal grain growth was found at the peripheral region near flash as well as stir zone in friction stir welding. Generally, the abnormal or drastic grain growth is caused by some reasons such as texture, prior deformation, residual stress, surface effect, precipitation phenomenon. The mechanism of abnormal grain growth in the friction welding is probably similar to that of FSW. Hassan et al. reported that the pinning particles would relate to microstructural stability of stir zone in FSWed AA7010 aluminum alloy.15) Sato et al. reported that drastic grain growth was not simple grain growth but accompanied nucleation and growth of newly formed grains, which related to inhomogeneous distribution of stored strain and crystallographic orientation.16) However, it has not been clarified completely yet. In the present study, no significant difference of Vickers hardness was found between central (HV77) and peripheral region (HV74) at the weld interface. On the other hand, mean grain size at the peripheral region at the weld interface was 2.6 μm, which is larger than that at central region (1.1 μm). The peripheral region showed similar hardness to that at central region despite of larger grain size. So in the case of friction welding, inhomogeneous prior deformation might be one of...
the reasons for the abnormal grain growth. In addition, since AZ31B includes second phase such as Al₆Mn, pinning effect would be considered. Anyway, further works on dislocation density and crystallographic orientation are necessary to clarify the abnormal grain growth mechanism in friction welded joint. However, the abnormal grain
growth area was limited and did not extend much at the higher temperature. Since the joints were worked for the tensile and fatigue tests as shown in Fig. 2, the influence of peripheral region on the mechanical properties must be negligible. So in the present study, we focused on just central region at the weld interface.

Figures 6 and 7 show the microstructural transition from weld interface to base metal along the central axis. As grain growth progressed, microstructure at each region changed from mixed grain to homogeneous. Two types of grain growth rate were found at each region. Faster grain growth like abnormal grain growth was observed in both work hardened region and base metal (Figs. 6(c) and 6(e)). When the base metal which is extruded bar was annealed, Vickers hardness decreased from HV65 to HV55. So the base metal already has additional hardness due to large dislocation density. The work hardened region could also contain lots of dislocations. Although the difference of dislocation density between base metal and the work hardened region has not been observed, the faster grain growth probably concerns to the effect of prior deformation and residual stress.17) On the other hand, faster grain growth was not observed in fine
Fig. 6 Microstructural transition from weld interface (a) to base metal (e) of heat treated joint for 1.8 ks at 573 K.

growed region and HAZ (Figs. 6(a) and 6(d)). Fine grained region and HAZ contained few dislocations. Since static recovery has already been completed in HAZ, normal grain growth occurred in spite of similar optical microstructure to base metal (Figs. 3(d) and 3(e)).

Figure 8 shows the plot of mean grain size at the center of
Weld interface as a function of heat treatment time. At the center of weld interface, mean grain size shows linear relation against the square root of time, which means normal grain growth occurs there. Although central region at the weld interface is a part of TMAZ in friction welding, the behavior of grain growth is different from that of stir zone of FSW. Park et al. reported the stir zone of friction welded magnesium alloy had fine equiaxed grains with a high density of dislocations.\textsuperscript{1)} Moreover, Shibayanagi et al. concluded the effect of residual stress introduced by a shoulder of FSW prove should be considered to discuss abnormal grain growth in a stir zone.\textsuperscript{17)} The difference of dislocation density and residual stress might be the reason why abnormal grain growth did not occur in the fine grained region of friction weld joint.

As a result, grain size could be controlled by heat treatment following friction welding although the area was very limited, that is, weld center.

Fig. 7 Microstructural transition from weld interface (a) to base metal (e) of heat treated joint for 7.2 ks at 773 K.

Fig. 8 Grain growth at the center of joint as a function of time at different temperature.
3.3 Mechanical properties

Figures 9 and 10 show typical stress strain curves of base alloy, as weld joint and heat treated joints. Table 2 shows tensile strength, 0.2% proof stress at weld interface, mean grain size at the weld interface, and fracture location. 0.2% proof stress was measured by strain gage at the weld interface. As weld joint was fractured in base metal and showed 100% joint efficiency although yield strength was decreased. Tensile strength was not affected by PWHT except for a joint made with 773 K/3.6 ks. The additional strength due to work hardening was removed by heat treatment of 773 K, resulting in lower tensile strength than that of base metal despite almost similar grain size to base metal. Since most joints were fractured not at the weld interface, the relation between mean grain size and tensile strength was not evaluated exactly.

Figure 11 shows the results of fatigue tests. The fatigue strength at $10^{7}$ of as weld joint was equal to that of base metal. However, heat treated joints that have similar grain size to base metal showed lower fatigue limit than that of base metal or as weld joint. This is because the effect of either work hardening or grain refinement did not work after heat treatment for fatigue strength as well as tensile strength. Further works must be necessary to investigate the effect of PWHT on fatigue properties.

4. Discussion

Several studies on the relation between grain size and strength such as hardness, tensile strength and yield strength of magnesium and magnesium alloys have been reported. It is well known classical Hall-Petch relation which shows linear relation of strength against $(\text{grain size}: d)^{-0.5}$ is found on most metals. However, magnesium alloys sometimes show non-linear relation between grain size and strength in the range of small grain size. AZ31B magnesium alloys with various grain size could be fabricated by adequate heat treatment following friction welding as described above as much as the controlled area is very limited. Figure 12 shows effect of grain size on micro Vickers hardness and yield strength of AZ31B magnesium alloy. Vickers hardness, 0.2% proof stress and grain size were measured at the weld center. The smallest grain size of 1.1 μm in Fig. 12 was found in the

<table>
<thead>
<tr>
<th>As received AZ31B</th>
<th>278.1</th>
<th>219</th>
<th>17.8</th>
<th>Base metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>As weld joint</td>
<td>281.7</td>
<td>135.5</td>
<td>1.3</td>
<td>Base metal</td>
</tr>
<tr>
<td>473 K/1.8 ks</td>
<td>281.1</td>
<td>135</td>
<td>1.6</td>
<td>Base metal</td>
</tr>
<tr>
<td>573 K/0.8 ks</td>
<td>281.9</td>
<td>141.5</td>
<td>3.3</td>
<td>Base metal</td>
</tr>
<tr>
<td>573 K/1.8 ks</td>
<td>281.9</td>
<td>100</td>
<td>6.4</td>
<td>Base metal</td>
</tr>
<tr>
<td>773 K/3.6 ks</td>
<td>260.7</td>
<td>82</td>
<td>14.6</td>
<td>Weld interface</td>
</tr>
</tbody>
</table>
Hall-Petch form, and in the nanocrystalline region the slope gradually decreases until it asymptotically approaches the flow stress of the grain boundaries.\textsuperscript{21} Especially, the tendency might be more remarkable for Mg which has hcp crystal structure than the other cubic metals. The major deformation mechanism of magnesium is based on a basal slip, resulting in less formability than cubic metals. That is to say, basal \(\alpha\) dislocation is dominant factor for deformation in grain interior. However, non-basal \(\alpha\) dislocation is active near grain boundaries. When the grain size is less than 7 \(\mu\text{m}\), not only basal \(\alpha\) dislocation but also non-basal \(\alpha\) dislocations are activated, resulting in better deformation.\textsuperscript{22} The mechanism illustrates the results in the present study.

5. Summary

The effect of post weld heat treatment on microstructures and mechanical properties of friction welded joints of magnesium alloy was investigated. Fine grained regions, work hardened region and heat affected zone were formed continuously from weld interface to base metal by friction welding. The minimum grain size of 1.1 \(\mu\text{m}\) was obtained at the center of weld interface. Although abnormal grain growth occurred at work hardened regions, normal grain growth was found at the center of weld interface by PWHT. Tensile strength and fatigue strength of as weld joints were equal to that of base metal. The effect of PWHT on the mechanical properties was most likely negligible until grain size increased to approximately 15 \(\mu\text{m}\).

The decrease in the Hall-Petch slope was found when the grain size decreased less than 3 \(\mu\text{m}\) in grain size in terms of yield stress.

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REFERENCES

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