CHAPTER 4  COFAAT METHOD FOR LV-EBW OF SIMILAR AZ-SERIES ALLOYS

This chapter examines interactions between the properties of three AZ-series magnesium alloys and welding conditions. Previous studies have left unanswered many questions regarding the joint efficiency, process window, optimum parameters, types of defect, empirical strength formulas, and weldment fracture modes of EBW of magnesium alloys. This chapter will clarify all these topics.

4.1  Tensile Test for SMW of AZ-Series Alloys

In this study, the tensile test played the most important role, which used a direct measurement of UTS of the weldment in order to understand the influences of beam current, accelerating voltage, welding speed and focal position. As shown in Figures 13 and 14, the UTS of AZ-series alloys clearly increases with Al content, beam current, and accelerating voltage, whereas it decreases with increasing welding speed. When the power is below 4000W, there is incomplete joint penetration, which results in occurrence of SC. But if the power is between 4000 and 5000 W, the strength of the samples remains constant over nearly the entire range studied. When the fixed accelerating voltage or beam current is individually changed to another value (30 or 40 kV, or 100 or 125 mA), a similar trend is obtained. However, whether the conditions are changed or not, the UTS of the NSC samples show no obvious difference and its curves were almost horizontal. For the reasons stated above, there was no other special phase transformation in the weld when a different amount of energy was input during EBW.

The effects of the focal position of the electron beam are indicated in detail by the appearance of the welds in AZ91D, as shown in Figure 15. When the focal position of the electron beam is close to the surface of the workpiece, it is easy to produce worse spatter on the surface, and this leads to more visible evidence of incomplete joint penetration at the root. This is because of the low melting point (650 °C) and boiling point (1090 °C) of pure magnesium; visible fluctuation in the weld can be caused by higher fluidity under conditions
Figure 13  Effects of beam current and welding speed on the UTS of AZ-series weldments.

Figure 14  Effects of accelerating voltage and welding speed on the UTS of AZ-series weldments.
Figure 15  Comparison of weld appearance for different focal positions in AZ91D plates (other fixed conditions: 113 mA, 40 kV, 73.3 mm/s).

of high energy density in EBW. After solidification, such areas will form obvious concavity and cause severe SC. The UTS values of the specimens for focal positions from top to bottom are 233.5MPa, 241.9MPa, and 266.0MPa in that order. Weldments in AZ31B (153.9MPa, 185.4MPa, and 234.1MPa) and AZ61A (175.5MPa, 242.8MPa, and 247.5MPa) showed the same trend as for AZ91D.

By comparing the workpieces for using the tensile test, we obtain the UTS of the base material, of the optimum SC weldment, and the average NSC weldment, as shown in Table 14. Values of the UTS of 78.8%, 83.2%, and 82.2% for the optimal SC weldment/base material ratios and of 91.1%, 96.2%, and 89.1% for the average NSC weldment/base material ratios are obtained when extruded plates of AZ31B, AZ61A, and AZ91D, respectively, were welded. Likewise, the optimum weldment/base material strain ratios for these alloys are 8.7%, 26.3%, and 25.8%. These results demonstrate that SC on the outside of the workpiece had an impact on the AZ31B, AZ61A, and AZ91D samples that was at least 12.3%, 13.0%, and 6.9%,
Table 14  A comparison of UTS, strain, and control parameters among the three AZ-series magnesium alloys and their optimum and worst weldments.

<table>
<thead>
<tr>
<th>Material (Matrix Strength, Strain)</th>
<th>Item</th>
<th>State</th>
<th>UTS of SC Weldment (Strain)</th>
<th>Ave. UTS of NSC Weldments</th>
<th>Welding Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ31B (296.9 MPa, 29.9%)</td>
<td>Optimum</td>
<td>234.1 MPa (2.6%)</td>
<td>270.5MPa</td>
<td>50 kV / 100 mA / 60.6 mm/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Worst</td>
<td>151.3 MPa (1.3%)</td>
<td></td>
<td>45 kV / 100 mA / 86.0 mm/s</td>
<td></td>
</tr>
<tr>
<td>AZ61A (297.4 MPa, 28.1%)</td>
<td>Optimum</td>
<td>247.5 MPa (7.4%)</td>
<td>286.0MPa</td>
<td>50 kV / 100 mA / 60.6 mm/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Worst</td>
<td>168.1 MPa (1.8%)</td>
<td></td>
<td>45 kV / 100 mA / 86.0mm/s</td>
<td></td>
</tr>
<tr>
<td>AZ91D (323.3 MPa, 22.9%)</td>
<td>Optimum</td>
<td>266.0 MPa (5.9%)</td>
<td>288.0MPa</td>
<td>40 kV / 113 mA / 73.3 mm/s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Worst</td>
<td>175.7 MPa (1.6%)</td>
<td></td>
<td>45 kV / 100 mA / 86.0 mm/s</td>
<td></td>
</tr>
</tbody>
</table>

Note: Focal positions are at the bottom of workpiece for all samples. The strength reported here is the UTS.

respectively, and the impact of both the HAZ and defects in the weld was 8.9%, 3.8%, and 10.9%, respectively. Meanwhile, they also indicate that in order of decreasing joint efficiency, the three materials may be ranked AZ61A, AZ91D, and AZ31B.

Figure 16 plots stress-strain curves for the base material, the optimum weld, and the worst weld for the alloys AZ31B, AZ61A and AZ91D. First, comparing the curves of the AZ-series base materials demonstrates that AZ31B has the highest yield strength; and exhibits necking during tensile testing. In contrast, AZ61A and AZ91D have UTS values equal to their fracture strength and exhibit no necking. Thus, it is clear that the UTS increases and the ductility decreases with increasing Al content in these alloys. Next, relative to the alloy matrix strength, we obtain UTS values of 51.0%, 56.5%, and 54.3% for the SC worst weldments/base material ratios of AZ31B, AZ61A, and AZ91D under the situation of complete joint penetration, respectively. Likewise, the worst weldment/base material strain ratios for these alloys are 4.3%, 6.4% and 7.0%. Although the strain ratio of the worst AZ91D weldment slightly exceeds that of the worst AZ61A weldment, the latter clearly reaches the highest UTS value. Hence, even in the worst case the joint efficiency of these materials remains in the order AZ61A, AZ91D, and AZ31B.
Figure 16  Stress-strain curves for the base materials, the optimum weld, and the worst weld in AZ alloys. (Table 14 gives the welding parameters of each sample.)

Figure 17  Distribution of UTS ratios for all weldments in the AZ-series alloys.
The process window (or parameter window) is an index describing the ease of meeting process requirements, and can be estimated by a method similar to that used to evaluate the joint efficiency. In this study, the distribution of UTS ratios (weldment/base material) for 75 sets of bottom-focused weldments of each alloy, as presented in Figure 17, can be used to determine the process window. At welding powers below 4000W, joint penetration is incomplete in all cases except for a few AZ61A and AZ91D weldments. Notably, the peak of the UTS distribution lies between 60% and 70% for AZ61A, and between 70% and 80% for AZ91D. The UTS distribution for AZ31B weldments, on the other hand, is approximately uniform over the range 30–70%. Furthermore, the number of weldments with a UTS ratio between 80% and 90% is only zero, four, and six for the AZ31B, AZ61A, and AZ91D alloys, respectively. All these data indicate that AZ91D has the best EBW process window of all three alloys, followed by AZ61A and then AZ31B.

The seventy-five UTS data points for each magnesium alloy were analyzed using nonlinear regression (we used the statistical software STATISTICA), and their regression curves are plotted in Figures 18–20. The analysis imposes a maximum power of 5000W, and only considers UTS values lower than the base material’s practical maximum. The $R^2$ statistic gives the probability that the predicted and experimental values are linearly correlated. The empirical formula used to predict the UTS is

$$U_{TS} = K \cdot \frac{V^a \cdot P^b}{U^c}, \quad (4-1)$$

where $K$ is the transfer coefficient. Table 15 presents the best-fit values of $a$, $b$, and $c$. The bands drawn in Figures 18–20 (dashed lines) represent a confidence level of 95%.

The electron beam current was measured in the generating assembly of the EBW equipment, so the total output power of the electron beam could be obtained directly. Based on formulae (2-2) to (2-3), the total efficiency of EBW and an estimate of $K$ can be derived as follows.

$$\eta^* = \eta \cdot \eta_e = \frac{P_f}{P}, \quad (4-2)$$

$$K \approx \eta^* \varphi. \quad (4-3)$$
Figure 18  UTS errors in a nonlinear regression analysis of AZ31B.

Figure 19  UTS errors in a nonlinear regression analysis of AZ61A.

Figure 20  UTS errors in a nonlinear regression analysis of AZ91D.
Table 15  Best-fit UTS formula parameters from a nonlinear regression analysis.

<table>
<thead>
<tr>
<th>Nonlinear Model equation</th>
<th>Coefficients</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$UTS = K \times V^a \times I^b / \nu^c$</td>
<td>$K$</td>
<td>$a$</td>
</tr>
<tr>
<td>AZ Alloys</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ31B</td>
<td>0.024</td>
<td>1.466</td>
</tr>
<tr>
<td>AZ61A</td>
<td>0.238</td>
<td>1.199</td>
</tr>
<tr>
<td>AZ91D</td>
<td>0.414</td>
<td>1.127</td>
</tr>
</tbody>
</table>

Eq. (4-3) relates the transfer coefficient $K$ to the transfer efficiency $\eta^*$ and the spot size $\varphi$ of EBW. It is therefore clear that there must be a close relationship between UTS and $\eta^*$. The UTS of a weldment has been found to increase continuously as the focal position moves from the surface to the bottom of a workpiece; that is to say, the UTS of a weldment is directly proportional to the spot size of the electron beam. Eq. (4-1) can therefore be very useful in determining practical EBW operating parameters for alloys in the AZ series.

Visual observations reveal that the fracture surfaces of all weldment tensile samples can be divided into two modes: an irregular FZ fracture, as shown in Figure 21(a), and a regular HAZ fracture, as shown in Figure 21(b). In the former mode, cracks running randomly across the middle of the weld are initiated and terminated in an undercut, HAZ, or root concavity; in the latter, a break occurs along the weld boundary. The histograms in Figure 22 show that 80.8% of the AZ31B weldments and 11.5% of the AZ91D weldments exhibited FZ fractures. In contrast, the two fracture modes were almost equally likely in the AZ61A weldments, with 48% exhibiting FZ fractures and 52% exhibiting HAZ fractures. These results suggest that microstructural changes in the weld influence the initiation and propagation of cracks in the AZ-series alloys. More precisely, the phase composition of the microstructure may be closely related to the elemental Al content.

### 4.2 Microstructure Observations on AZ-Series Similar Welds

Direct observation of microstructure is the most important method of determining the fracture mode. Figure 23 displays cross-sectional metallographs of the optimum (Figures 23(a)-(c)) and worst (Figures 23(d)-(f)) welds in all three alloys. Cavities (arrows), undercuts
Figure 21  Schematic of EBW fracture modes in the AZ-series magnesium alloys.

Figure 22  Histogram of weld fracture modes in the AZ-series magnesium alloys.

Figure 23  Cross-sectional metallographs of the optimum and worst welds of all three AZ-series alloys. (Table 14 presents the parametric conditions of each sample.)
(circles), and root concavities (ellipses) are all fatal factors that can cause excessive SC in a poor weld, and reduce the UTS of the weldment.

Figures 24(a)-(c) show SEM photographs of the optimal weld boundaries, magnifying the rectangular regions indicated in Figures 23(a)-(c). Many precipitates concentrate in the FZ, in a distribution that tends to grow from a few scattered particles to densely packed dendrites as the Al content increases. Using EDS analysis, as displayed in the lower left corners of Figures 24(a)-(c), the chemical compositions of these precipitates with more Al and Zn content than that of the base material are moved from the vicinities of these precipitates. Furthermore, EPMA analysis yields some line scan curves across the top, middle, and bottom weld boundaries as presented in Figure 25. The Mg and Al content (vertical axis) in the FZ fluctuates as expected, since many precipitates form there. The number of such precipitates increases with Al content (Figures 25(a)-(f)). Additionally, local differences in the input energy and heating time cause the number of precipitates to decrease from the top to the bottom of the FZ (Figures 25(e)-(j)). Clearly, the distribution of precipitates affects the mechanical properties of the weldments and changes the probable fracture mode.

4.3 XRD Analysis on AZ-Series Similar Welds

The preferred orientation and special phases of AZ-series magnesium alloys can be analyzed by XRD. As shown in Figures 26(a)-(c), the (1 0 1 0) plane which lies on the transverse plane of the extruded plate is the preferred orientation of all alloys before EBW. The peak intensity of this direction decreases as the Al content of the alloy increases. After EBW, the forging structure is converted to a casting structure and the original preferred orientation has disappeared in the weld. The preferred orientation of a casting structure, such as the (1 0 1 1) peak seen in Figures 26(d)-(e) which is not as obvious as that of a forging structure, even though affected slightly by epitaxy growth along the weld boundary. The γ phase is the sole intermetallic compound, but its peak is not well marked either before or after welding for any choice of operating parameters.
Figure 24  SEM enlargements of the weld boundary regions shown in Figures 23(a)-(c).
(Lower left: an enlargement of the photograph obtained by EDS analysis.)
The observations described in the last few paragraphs indicate that the distribution of the brittle $\gamma$ phase changes from scattered particles to dense dendrites as the Al content increases. At the same time, the strength of the FZ increases and the preferred fracture mode changes from FZ to HAZ. The ductility of the optimum weldment does not improve, however, because only the brittle $\gamma$ phase forms microstructures in the FZ.

Figure 25  EPMA analysis of the optimum weld boundaries for each AZ-series magnesium alloy. (Table 14 gives the parametric conditions of each sample)
4.4 Microindentation Hardness Test for SMW of AZ-Series Alloys

Figures 27(a) and (b) present the positions and results of microindentation hardness testing on the weld cross-section. Microindentation hardness values for the FZ, HAZ, and base material increase with increasing Al content in the magnesium alloy. The brittle γ phases are found mainly in the center of the upper weld, and their spatial distribution causes the hardness to decrease towards the bottom of the sample and away from the FZ axis. Both the vertical and horizontal test results agree with the curves obtained by EPMA analysis. Moreover, a comparison of the optimum and worst weldments clearly shows that the curve of the former is more symmetrical than that of the latter. The reason might be that the soften effect of coarse grain and the existence of cavities in the weld together caused the larger area of indentation and thus influenced the test value of the microindentation hardness. Hence, at random positions the microindentation hardness of the weld may decline suddenly, for
example at the points (-1.5, 5.0), (0.5, 0) and (0, -5.0).

All the observations mentioned above support our previous deductions concerning the nature of the fracture modes. The crack is initiated at an undercut, HAZ, or root concavity, and then propagates either along the HAZ boundary or through the FZ by linking cavities or softening zones. Finally, the probability of FZ and HAZ fractures is determined by the distribution of precipitates with Al content in AZ-series magnesium alloys.

Figure 27 Microindentation hardness testing of the weld cross-section in AZ-series magnesium alloys.

(a) The sketch of test positions of microindentation hardness.

(b) The results of microindentation hardness test for the weldments of AZ series magnesium alloys.