2.1 Brief Review of Mg-Al-Based Alloys

Of the lightweight metals, magnesium alloys and aluminum alloys are considerably important structural materials due to their properties of low density and high specific strength. Their costs are lower than those of titanium alloys, and the amount of use is very respectable, which are major considerations for selecting materials.

Magnesium-Aluminum-based alloys are often compared with engineering plastics for various applications. The former may be better than the latter in terms of their physical and mechanical properties [21]. For example, when components are made with Mg-Al-based alloys to obtain specific strengths comparable to engineering plastics, sometimes the former can be lighter than the latter. Additionally, the recycling of engineering plastics is still an unresolved issue in the field of environmental protection. In this situation, many countries have legislated against the use of engineering plastics, while the use of Mg-Al-based alloys has increased year by year. The potential for application of magnesium alloys can be foreseen from these facts.

2.1.1 Metallurgy techniques and process development

Magnesium alloys were not developed until long after D. Black first discovered the Mg element in 1755. H. Davy first extracted magnesium oxide from the mixture of Hg and MgCl$_2$ in 1808, which scientists recognize as the birth date of magnesium [2]. In 1828, A. Bussy fused MgCl$_2$ with potassium to obtain magnesium, and M. Faraday accomplished the first production of magnesium by electrolytic reduction from MgCl$_2$ in 1833 [1,22].

Magnesium, which is a silver alkaline earth metal with three isotopes [1,4], is the sixth most abundant element (about 2.5%) on the Earth’s surface and the third most plentiful element (about 0.14%) in seawater. Pure magnesium is very resistant to corrosion by alkalis when the PH exceeds 10.5. However, it can be attacked easily by most acidic solutions (even organic solutions such as methyl alcohol and glycol) [2]. Table 1 shows the properties of four
common structural metals [23,24]. Pure magnesium is widely used in alloying elements, fireworks, flash lights, sacrificial anode materials, and batteries, but it is rarely used in engineering structures. Like other metals, magnesium can be alloyed with other elements for specific purposes. Magnesium alloy ingots and billets can then be fabricated further.

Designers first used pure magnesium as a structural material in 1909. Because of its low room temperature strength (about 186MPa), Al and Zn elements were added to form Mg$_{17}$Al$_{12}$ ($\gamma$ phase, $T_m$=437°C) and MgZn ($T_m$=347°C) phases. This raises magnesium’s mechanical properties via solution strengthening and precipitation hardening [22]. During World War I, Germany used Mg-Al-Zn casts extensively in its rapid aerospace industry development [25]. Meanwhile, mass production of fire bombs also increased the demand for magnesium. In 1916, the first factory was built by Dow Chemical Company in America [26], which extracted pure magnesium from sea water using the typical electrolytic process [22].

Table 1 Comparisons between four common structural metals [23,24].

<table>
<thead>
<tr>
<th>Properties</th>
<th>Mg</th>
<th>Al</th>
<th>Ti</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td>12</td>
<td>13</td>
<td>22</td>
<td>26</td>
</tr>
<tr>
<td>Atomic weight</td>
<td>24.31</td>
<td>26.98</td>
<td>47.90</td>
<td>55.84</td>
</tr>
<tr>
<td>Crystal structure (20°C)</td>
<td>HCP</td>
<td>FCC</td>
<td>HCP</td>
<td>BCC</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>1.74</td>
<td>2.70</td>
<td>4.51</td>
<td>7.87</td>
</tr>
<tr>
<td>Specific heat (J/kg·K)</td>
<td>1360</td>
<td>1080</td>
<td>523</td>
<td>795</td>
</tr>
<tr>
<td>Latent heat(10$^3$J/kg)</td>
<td>3.7</td>
<td>4.0</td>
<td>–</td>
<td>2.7</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>650</td>
<td>660</td>
<td>1670</td>
<td>1538</td>
</tr>
<tr>
<td>Boiling point (°C)</td>
<td>1090</td>
<td>2450</td>
<td>3290</td>
<td>2860</td>
</tr>
<tr>
<td>Surface tension (N/m)</td>
<td>0.559</td>
<td>0.914</td>
<td>1.650</td>
<td>1.872</td>
</tr>
<tr>
<td>Viscosity (mPa·s)</td>
<td>1.22</td>
<td>1.90</td>
<td>–</td>
<td>6.37</td>
</tr>
<tr>
<td>Thermal conductivity (W/cm$^2$·°C)</td>
<td>1.56</td>
<td>2.37</td>
<td>0.22</td>
<td>0.80</td>
</tr>
<tr>
<td>Thermal expansibility (µm/m·°C)</td>
<td>26.6</td>
<td>23.5</td>
<td>8.4</td>
<td>12.0</td>
</tr>
<tr>
<td>Thermal diffusivity (10$^3$m$^2$/s)</td>
<td>37.3</td>
<td>36.5</td>
<td>–</td>
<td>6.8</td>
</tr>
<tr>
<td>Relative specific strength</td>
<td>1.00</td>
<td>0.75</td>
<td>1.30</td>
<td>0.50</td>
</tr>
<tr>
<td>Electronic conductivity (%IACS)</td>
<td>40</td>
<td>64</td>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>Damping property</td>
<td>25%</td>
<td>1%</td>
<td>0.3%</td>
<td>17%</td>
</tr>
<tr>
<td>Vapor pressure (mmHg)</td>
<td>Mg</td>
<td>Al</td>
<td>Ti</td>
<td>Fe</td>
</tr>
<tr>
<td>1 mmHg =133.322Pa</td>
<td>log P=-7550/T-1.41logT+12.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range is from melting to boiling temperature. T: absolute temperature</td>
<td>Al log P=-16380/T-1.0logT+12.32</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti log P=-23200/T-0.66logT+11.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe log P=-19710/T-1.27logT+13.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
After World War I, all countries in Europe started using Mg-Al-Zn alloys to reduce the weight of their fighter planes, but these alloys suffered from corrosion problems in wet or moist environments. In 1925, this serious problem was amended slightly by the discovery that small amount of Mn could be added to Mg-Al-Zn alloys [25], and high strength AZ91A alloy was developed in 1927.

In 1930, magnesium alloy was first used for bicycle wheels. Volkswagen (VW) made the first air-cooled engine with magnesium alloys for automobiles and motorcycles in 1934 and 1938, respectively [27]. This was a milestone for the application of magnesium alloys and the pursuit of lightweight vehicles. During World War II, magnesium alloys were in great demand again. L. M. Pidgeon developed a high temperature process in 1941 to reduce the mixture of ferrosilicon and dolomite ($\text{MgCO}_3\cdot\text{CaCO}_3$) under a vacuum [1,22]. This process produced volatile Mg, which distilled off and was collected in a container. This procedure laid the foundations of the thermal reduction method. In 1942, the first magnesium manufacturing plant was established in Canada [1,26].

In the 1950’s, America fabricated F-100 fighters which used magnesium alloys as major materials. Thereafter, magnesium alloys were replaced by aluminum alloys and titanium alloys due to their low cost and high strength, respectively. The major applications of magnesium alloys were then switched to civil purposes such as vehicle and sporting goods. Examples of this are AZ91, AZ81A, and AZ61A. Because AZ91 alloys have poor ductility, they were not useful in vehicle wheel applications until some researchers reported in 1960 that the addition of Ca to Mg-Al-Zn alloy improved its tensile strength and creep resistance with fine grains at elevated temperature [25]. Also, the AZ81A alloy with higher ductility and impact value was also developed for use in wheels. When required to be electroplated, AZ61A with an optimal combination between strength and ductility had a better effect [1,21,28].

Because the Mg-Al-Zn alloys could not provide the properties required for their applications, in the last half century, the development of magnesium alloys mainly focused on the addition of alloying elements such as Si, Mn, and RE, which raise greatly the mechanical properties [2,22,25,28]. Some researchers also found that Fe, Ni, and Cu easily form
intermetallic compounds in the grain boundary of magnesium alloys. These elements act as microscopic cathodes, destroying the protective oxide film and reduce corrosion resistance [22,25]. Die-casting high purity AZ91D alloy was developed in the 1990’s, and this approach has much better corrosion resistance in salt fog test (about 100 times better) than AZ91C. Stress corrosion problems cause hydrogen embrittlement inducing transgranular fractures, which can also be amended. Using AZ91E in gravity casting shows a corrosion rate similar to AZ91D [2].

In 1993, the American government made a plan about the Partnership for a New Generation of Vehicles (PNGV) with Ford, GM, and Chrysler companies to develop aggressively automobile parts and assemblies using magnesium alloys [27]. In 1995, the government of Germany also announced a DM 25 million ($17 million), three-year magnesium research program to be jointly financed with industry. The goal of the MADICA program was to further develop and optimize magnesium alloy products and processes [29]. There was a watershed for the application of magnesium alloys in 1997. The shell and inner parts of notebook computers were first made with magnesium alloys in Japan, and received a warm reception. Taiwan and Korea followed close behind in more applications, such as mobile phones and PDAs.

Due to plentiful magnesium ores and aggressive mining, China has been the world’s largest pure magnesium exporting country (more than 90% of it made by the Pidgeon method) since 1999. Under low price competition, America was opposed to slashing its production. According to statistical information from 2002, 95% of magnesium-made products were fabricated in die-casting processes. Nearly 90% of die-casting products were made with Mg-Al-Zn and Mg-Al-Mn alloys: 72.2% were used for automobiles in Europe and 20.4% used for 3C products in Asia. From the viewpoint of economic efficiency or industrial application, magnesium alloys can create boundless commercial opportunities in the future if forging processes are planned and developed further.

2.1.2 Alloy designation and classification

An international designation of magnesium alloys does not exist, and all users
currently use the American Society for Testing Materials standard. This standard is a three-part letter-number-letter system. In sequence, the first two letters are the principal code for added elements, as Table 2 shows. The following numbers represent both nominal element contents as a percentage of weight. Suffix letters (A, B, C, etc.) indicate the upgrading code, and X indicates an experimental alloy. Additionally, heat treatment and work hardening conditions use the same standard as aluminum alloys [1,2].

Magnesium alloys and aluminum alloys share many similar properties, such as a strong tendency to oxidize, high thermal expansibility, low melting point temperature, and no color change during melting [4,30]. Magnesium alloy is becoming one of the most important lightweight materials because of its low density, high specific strength, good thermal and electronic conductivity, superior castability and weldability, excellent properties for absorbing vibration and insulating electromagnetic interference [22], which are suitable for the design of lightweight products. However, magnesium’s usability is less than that of other engineering materials such as steel and aluminum alloys due to its high metallurgy cost, poor formability, and low corrosion resistance [31]. Forged products are only 5% magnesium alloys, but their superior mechanical properties will lead to numerous applications.

Chemical composition determines the material property, workability, and heat treatment of magnesium alloys. This is because precipitates can be dispersed uniformly by precipitate hardening. Meanwhile, the Orowan mechanism is useful for producing high strength at elevated temperatures. Currently there are four series of magnesium alloys used

<table>
<thead>
<tr>
<th>Code</th>
<th>Element</th>
<th>Code</th>
<th>Element</th>
<th>Code</th>
<th>Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Aluminum</td>
<td>K</td>
<td>Zirconium</td>
<td>S</td>
<td>Silicon</td>
</tr>
<tr>
<td>B</td>
<td>Bismuth</td>
<td>L</td>
<td>Lithium</td>
<td>T</td>
<td>Tin</td>
</tr>
<tr>
<td>C</td>
<td>Copper</td>
<td>M</td>
<td>Manganese</td>
<td>W</td>
<td>Yttrium</td>
</tr>
<tr>
<td>D</td>
<td>Cadmium</td>
<td>N</td>
<td>Nickel</td>
<td>Y</td>
<td>Antimony</td>
</tr>
<tr>
<td>E</td>
<td>Rare earths</td>
<td>P</td>
<td>Lead</td>
<td>Z</td>
<td>Zinc</td>
</tr>
<tr>
<td>F</td>
<td>Iron</td>
<td>Q</td>
<td>Silver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>Thorium</td>
<td>R</td>
<td>Chromium</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2  Alloying element code for magnesium alloys [1,2].
commercially in casting and forging: Mg-Al-Zn (AZ-series), Mg-Al-Mn (AM-series), Mg-Al-Si (AS-series), and Mg-Al-RE (AE-series). Tables 3 and 4 show the classification, characteristics, applications, and alloying effects for magnesium alloys. Take the AZ-series alloys for example. As the Al content increases up to 9 wt.%, alloy strength by fine grain and precipitated $\gamma$ phase increase, but the ductility decreases. Meanwhile, the strength of AZ-series alloys can be increased slightly with up to 1 wt.% Zn; otherwise Zn elements will stay in the grain boundary and induce hot cracking [32]. Therefore, high Zn magnesium alloys are not suitable for welding processes.

2.1.3 Casting and forging processes

The manufacturing technology of magnesium alloys is differentiated into casting and forging. The former includes sand casting, gravity casting, squeeze casting, and die casting; the latter includes extrusion, rolling, and press forging [2,33]. Regardless of whether casting or forging is used, workpieces can be riveted and welded together.

Due to the high chemical activity and poor formability of magnesium alloys, the casting process is a suitable way to fabricate complex workpieces. Squeeze-casting is an excellent method for producing pressure-sealed, low-porosity, weldable, heat-treatable parts with reproducible high quality. Since its casting speed is very slow, however, it is not applicable to high-volume production [21,27]. Therefore, most magnesium alloy components are currently produced by the die-casting process [34]. Die-casting is a near net shape casting process created by C. Babbage in 1868. It can be used for all materials with a melting point below 800°C, and is especially suitable for thin and complex precision parts. Because magnesium alloys have superior fluidity, low density, and specific heat, the life time of the die and the output of products can be increased by low die wear and fast cycle times. Vacuum die-casting processes can also effectively address porous problems [2,4,21,27,35].

Conventional die-casting process of magnesium alloys can be classified into hot- and cold-chamber die casting. A hot chamber machine is usually used for alloys with a low melting point. Its gooseneck and shot cylinder are immersed in the molten alloy, thereby maintaining the die at a fixed pouring temperature. Because the flowing metal hardly comes
# Table 3  Classification, characteristics, and applications for AZ-series alloys.

<table>
<thead>
<tr>
<th>Process</th>
<th>Alloy</th>
<th>Properties</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forgining material</td>
<td>AZ10</td>
<td>Moderate strength, low cost.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AZ21</td>
<td>Good weldability, α phase alloy.</td>
<td>Impact-extruded battery anode.</td>
</tr>
<tr>
<td></td>
<td>AZ31</td>
<td>AZ31B with good formability, weld-ability, medium strength, high corrosion resistance and elongation can be hammer forged. AZ31C is similar to AZ31B but higher impurity limits (extruded material: 262MPa, strain: 14%).</td>
<td>Bicycle: wheel, handle bar. Automobile: seat frame. Other: photoengraving (PE) plate.</td>
</tr>
<tr>
<td></td>
<td>AZ42</td>
<td>Good mechanical properties, moderate cost, excellent weldability. Stress relief is required. This alloy can be artificially aged. (extruded material: 317MPa, strain: 17%).</td>
<td>Automobile: transmission case, cylinder head cover.</td>
</tr>
<tr>
<td></td>
<td>AZ61</td>
<td>Castable material, good strength, ductility and toughness, poor weldability.</td>
<td>Bicycle: crank, handle bar, frame. Automobile: parking brake level, wheel, kickstand. Other: electrode plate.</td>
</tr>
<tr>
<td></td>
<td>AZ63</td>
<td>Stronger than AZ61A; good forgability and weldability. (extruded material: 338MPa, strain: 12%).</td>
<td>Airplane: engine cover plate. Other: an anode for cathodic protection of steel structure.</td>
</tr>
<tr>
<td></td>
<td>AZ80</td>
<td>Good strength, weldability and castability, excellent ductility and toughness, fair weldability, low microshrinkage tendency, good forgability (cast-T4: 275 MPa, cast strain: 15%).</td>
<td>Bicycle: crank, handle bar, frame. Automobile: wheel.</td>
</tr>
<tr>
<td></td>
<td>AZ81</td>
<td>Good strength, weldability and castability, excellent ductility and toughness, fair weldability, low microshrinkage tendency, good forgability (cast-T4: 275 MPa, cast strain: 15%).</td>
<td>Automobile: wheel.</td>
</tr>
<tr>
<td>Casting material</td>
<td>AZ91</td>
<td>AZ91A, AZ91B with low cost and poor corrosion resistance are used in die casting, but AZ91C is sand and permanent-mold casting. AZ91D and AZ91E with high purity and excellent corrosion resistance have high strength. AZ91D is die casting alloy, but AZ91E is sand and permanent-mold casting. Only AZ91C and AZ91E can be welded with filler metals. Stress relief is required (cast-T4: 275 MPa, cast strain: 15%).</td>
<td>Bicycle: wheel, pedal. Motorcycle: wheel. Automobile: valve cover, wheel, case housing, steering wheel, steering column bracket, drive bracket, oil pan, clutch housing, clutch and brake pedal, cylinder head cover, cylinder block, oil sump, gearbox housing, cylinder head, intake manifold, transfer case. Other: mobile-phone case, notebook computer shell.</td>
</tr>
<tr>
<td></td>
<td>AZ92</td>
<td>Sand and permanent-mold casting alloys with high strength can be welded with filler metal. Stress relief is required. (cast-T4: 275 MPa, cast strain: 10%).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AZ101</td>
<td>Weldable.</td>
<td>Experimental material.</td>
</tr>
<tr>
<td></td>
<td>AZ501</td>
<td>Single phase (β) alloy.</td>
<td>Experimental material.</td>
</tr>
<tr>
<td>Element</td>
<td>Melting, casting, and welding properties</td>
<td>Mechanical and technological properties</td>
<td>Corrosion behavior</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------------</td>
<td>----------------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>Al</td>
<td>Improves castability, refines grain, tendency to microporosity.</td>
<td>Improves strength and hardness below 120°C, but lower ductility, 6wt% yield the optimum combination of strength and ductility.</td>
<td>Minor influence</td>
</tr>
<tr>
<td>Zn</td>
<td>Increases fluidity of the melt (12–15wt.%), weak grain refiner, tendency to microporosity.</td>
<td>Improves strength below 120°C, tendency to brittleness and hot shortness (1.5–12wt.%), unless Zr refined.</td>
<td>Minor influence, overcome the harmful effect of Fe and Ni impurities.</td>
</tr>
<tr>
<td>Mn</td>
<td>Removes heavy-metal elements into harmless intermetallic compounds, refines precipitates.</td>
<td>Increases strength, ductility, and creep resistivity.</td>
<td>Improves corrosion behavior.</td>
</tr>
<tr>
<td>Si</td>
<td>Increases fluidity, decreases castability, forms stable Si compounds with other alloying elements, compatible with Al, Zn, and Ag, weak grain refiner.</td>
<td>Improves creep property.</td>
<td>Detrimental influence.</td>
</tr>
<tr>
<td>Ca</td>
<td>Reduces oxidation slightly during melting, cracking easily above 0.3wt.% during welding.</td>
<td>Suppress γ phase, refining grain, improves creep property below 0.3wt.%</td>
<td>Lowers salt-water corrosion resistance.</td>
</tr>
<tr>
<td>Cu</td>
<td>System with easily forming metallic glasses, improves castability.</td>
<td>Improves high temperature property.</td>
<td>Adverse effect above 0.05wt.%</td>
</tr>
<tr>
<td>Li</td>
<td>Increases evaporation and burning behavior, melting only in protected and sealed furnaces.</td>
<td>Solid solution hardener at ambient temperatures, reduce density and strength, enhances ductility, age hardening above 60°C.</td>
<td>Lowers corrosion resistance, surface treatment necessary</td>
</tr>
<tr>
<td>Th</td>
<td>Improves weldability of alloys containing Zn.</td>
<td>Most effective element for improving strength, creep, and ductility below 370°C.</td>
<td>Classify as radioactive materials above 2wt.%</td>
</tr>
<tr>
<td>Y</td>
<td>Grain refining effect.</td>
<td>Improves elevated temperature properties below 300°C.</td>
<td>Improves corrosion behavior.</td>
</tr>
<tr>
<td>RE</td>
<td>Forms intermetallic compounds to stabilize grain boundary, reduces weld cracking and porosity in casting.</td>
<td>Improves high temperature property by solution and precipitating hardening.</td>
<td>Improves corrosion behavior.</td>
</tr>
<tr>
<td>Zr</td>
<td>Most effective grain refiner, incompatible with Si, Al, and Mn, remove Fe, Al, and Si from the melt.</td>
<td>Improves ambient temperature tensile properties slightly.</td>
<td></td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td>Improves mechanical properties, increases response to age hardening.</td>
<td>Detrimental influence.</td>
</tr>
<tr>
<td>Fe</td>
<td>Magnesium hardly reacts with mild steel crucibles.</td>
<td></td>
<td>Limits below 0.005wt.%</td>
</tr>
<tr>
<td>Ni</td>
<td>Forms harmful impurities in Mg alloys, system with easily forming metallic glasses.</td>
<td></td>
<td>Limits below 0.005wt.%</td>
</tr>
<tr>
<td>Be</td>
<td>Significantly reduces oxidation of melt surface below 30ppm, leads to coarse grains.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
into contact with air, very little air is entrapped. Therefore, a hot-chamber machine is more competitive than cold-chamber machines for thin-walled (e.g. 2mm) 3C products because of its shorter cycle times [1]. In cold-chamber machines, neither the metal chamber nor the plunger is heated. This technique is often used for alloys with a high melting point. The liquid metal passes into the cold chamber via a scooping tool or by means of a proportioning furnace, and then injected into a die. Cold-chamber machines are applicable for large castings (≥10kg) [2.27] such as the parts of dynamo-electronic tools and automobiles, though its product quality and output are lower than hot-chamber machines.

The mechanical properties of forged materials are generally better than those of casted materials. Affected by hexagonal close packed (HCP) structures below 225°C, a slip system only includes the (11\bar{2}0) direction on the basal plane (0001) and the prismatic plane \{10\bar{T}0\}. Meanwhile, twin occurs on the pyramidal \{10\bar{2}2\} and \{30\bar{3}4\} planes. These limitations increase the workpiece hardening rate and lower its ductility, which can be amended above 225°C. The additional (11\bar{2}0) direction on the pyramidal \{10\bar{T}1\} slip planes becomes operative, increasing the formability slightly [1,2,21,22,36]. Despite this, the formability of magnesium alloys is still behind that of other engineering materials. Increasing the temperature raises the product reliability only slightly, and impact speed, die cleaning, and lubrication must be considered simultaneously [37]. In other words, magnesium alloys may change phase structures from HCP to body-centered cubic (BCC) by means of alloying elements such as Li (but lower strength) to solve the problem of poor slip system [21]. The impact forging process of magnesium alloys may be very difficult to apply widely.

The forgeability of magnesium alloys depends on its solidus temperature, deformation rate, and grain size. Generally, magnesium alloys with small-sized grains are forged easily by a slow deforming rate within 55°C of the solidus temperature [1]. Thermo-mechanical treatments are therefore the most applicable for magnesium alloys [38], and hot extrusion is the most common process. Extrusion temperatures used for magnesium and its alloys typically range from 300 to 450°C, and cross sectional area reductions range from 10 to 1 to 100 to 1 [1,2]. There is apparently a flow microstructure in the extrusive direction [39]. Hot extrusion processes can also improve the mechanical properties of magnesium alloys because
the grain is fine, below 10µm. When grains measure less than 1µm, twin formation can be depressed to greatly increase workability [40]. According to the ANOVA results of Taguchi’s method, the importance of extrusion parameters for AZ31B and AZ61A is affected by process temperature, material difference, lubricant type, and extrusion speed, in order of impact [41].

2.1.4 Phase diagram and heat treatment

Melting magnesium can dissolve hydrogen up to 60ppm at 800°C, and its solubility drops further from 40ppm (liquid state) to 24ppm (solid state) during solidification at 650°C. Generally, the hydrogen content of die-casting magnesium alloys is only 8ppm after performing heat treatment, which is still much more than in pure Al (<0.01ppm) [13]. High purity materials can be produced using vacuum melting equipment to expel all gases and reduce the possibility of forming harmful non-metallic inclusions [42]. Additionally, a little additional Be (10–30ppm) helps to reduce the magnesium alloy oxidation [25].

The mechanical properties of most magnesium casting alloys can be amended by heat treatment, but only AZ, ZK, and ZC series forging alloys are thus treated. Because most magnesium forming operations are performed at elevated temperatures, a fully annealed process is seldom adopted. Under high-precision requirements, a low stress-relieving temperature and long heating time should be used to minimize distortion. To avoid remelting eutectic compounds and combining voids, the solution-treating temperature should be raised slowly [1]. Tables 5 and 6 show the heat treatment parameters for prewelding and postwelding.

Since the Al content of commercial Mg-Al alloys is lower than 10.0 wt.%, the δ (solid solution phase) and γ (Mg17Al12) phases, which are the dominant phases, will be the two most important components [1]. In the Mg-Al binary phase diagram (Figure 1 [43]), the maximum solid solubility of aluminum is 12.7 wt.% at 437ºC decreasing to about 2.0 wt.% at room temperature [2]. With increasing the Al content, if the alloy is cooled quickly from the melting point to room temperature, more Al atoms will be dissolved in the δ phase and more of the discontinuous γ phase will be formed along grain boundaries [44,45]. If a solution treatment is performed near 430ºC, the γ phase gradually dissolves into the δ phase and produces the
Table 5  Heat treatment parameters for Mg-Al alloys [1].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Alloys</th>
<th>Stress relief</th>
<th>Solution treatment (T4)</th>
<th>Aging (T5)</th>
<th>Aging (T6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Teens.</td>
<td>Time (°C)</td>
<td>Time (hr)</td>
<td>Max. temp.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(°C)</td>
<td>(°C)</td>
<td>(hr)</td>
<td>(°C)</td>
</tr>
<tr>
<td></td>
<td>AZ31B</td>
<td>&gt;1</td>
<td>260°C</td>
<td>F</td>
<td>100°C</td>
</tr>
<tr>
<td></td>
<td>AZ31C</td>
<td>&gt;1</td>
<td>260°C</td>
<td>F</td>
<td>100°C</td>
</tr>
<tr>
<td></td>
<td>AZ61A</td>
<td>&gt;1</td>
<td>260°C</td>
<td>F</td>
<td>0.25°F</td>
</tr>
<tr>
<td></td>
<td>AZ63A</td>
<td>–</td>
<td>260°C</td>
<td>F</td>
<td>100°C</td>
</tr>
<tr>
<td></td>
<td>AZ80A</td>
<td>&gt;1</td>
<td>260°C</td>
<td>1°F</td>
<td>1°F</td>
</tr>
<tr>
<td></td>
<td>AZ81A</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>413</td>
</tr>
<tr>
<td></td>
<td>AZ91C</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>413</td>
</tr>
<tr>
<td></td>
<td>AZ92A</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>407</td>
</tr>
</tbody>
</table>

※Note 1: The suffixal symbol is temper designation. Here the information refers to a 25mm-thick workpiece, but the time should be doubled for a 50mm-thick workpiece (also depend on grain growth).
※Note 2: Stress relief parameters after welding AZ and AM series casting alloys are all 260°C-1hr. With regard to solution treatment above 400°C, it requires a protective atmosphere, and then quenches in air.

Table 6  Parameters of heat treatment for welding Mg-Al alloys [1,27].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Alloys</th>
<th>Filler metal</th>
<th>Temper before welding</th>
<th>Preheating</th>
<th>Solution treatment (T4)</th>
<th>Aging (T6)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Temp. (°C)</td>
<td>Rate (°C/hr)</td>
</tr>
<tr>
<td></td>
<td>AZ63A</td>
<td>AZ92A</td>
<td>F</td>
<td></td>
<td>385</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T4</td>
<td></td>
<td>385</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T6</td>
<td></td>
<td>385</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>AZ81A</td>
<td>AZ92A or AZ101</td>
<td>T4</td>
<td></td>
<td>413</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>AZ91C</td>
<td>AZ92A or AZ101</td>
<td>T4</td>
<td></td>
<td>413</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>T6</td>
<td></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>AZ92A</td>
<td>AZ92A</td>
<td>T4</td>
<td></td>
<td>407</td>
<td>0.5</td>
</tr>
</tbody>
</table>
maximal ductility. Aging at 150–250°C produces some γ phase precipitations within the grain without forming Guinier-Preston zone and a further small increase in tensile strength and hardness, but ductility is reduced slightly [1,2,25].

When the Al content exceeds 12.7wt.%, two intermetallic compounds gradually dominate over the mechanical properties of magnesium alloys: β (Mg$_2$Al$_3$, $T_m$=450°C) and γ phases. Both phases are complex face-centered cubic (FCC, Fd$\bar{3}$m) and BCC (I4$\bar{3}$m) structures which coexist heterogeneously in Mg-Al binary alloys, respectively [46]. Because they have different thermal expansibilities, these brittle phases easily induce cracks during cycling thermal stress. Additionally, Mg-Al binary alloys contain many high-temperature phases and metastable phases, whose existing conditions cannot be completely identified [47]. If Zn is added, the Mg-Al-Zn ternary alloy produces many complex phase transformations [48-50] and unknown influences in welding AZ-series alloy processes.
The mechanical properties of AZ-series alloys decrease rapidly above 125°C as grain sliding and γ phase softening causes creep in magnesium alloys. The addition of 1wt.% Ca can improve this situation, but makes the alloy susceptible to hot cracking [25]. Creep properties are also amended by decreasing the Al content and introducing Si, Mn, or RE [2,22,25,28]. The improved properties could withstand at least 175°C because these elements reduce the amount of γ phase around the grain boundary and form fine stable particles of Mg$_2$Si ($T_m=1085°C$ [22]) and Al$_2$RE compounds which decrease grain boundary sliding [2]. These improvements greatly extended magnesium alloy applications.

In summary, increasing mechanical properties and formability at elevated temperatures are the most important factors for magnesium alloys. Before capturing these factors, producing a complex assembly with magnesium alloy can be accomplished temporarily by combining simple forged parts under appropriate welding conditions to meet lightweight requirements.

2.2 Overview of Electron Beam Welding

Created in the industry in the 1950's, EBW has reached its zenith during the last several decades. In contrast, the first commercial scanning electron microscope (SEM) was also made in 1965, inaugurating a nanometer age. In inner structure and operating principle, both devices are similar to each other. The former is good at joining workpieces with higher energy density, and the latter enables image resolution on the nanometer scale.

Limited by welding precision until the ending of the 20th century, EBW equipment could only deal with workpieces 0.1mm wide and thick, which seems to have reached a bottleneck in EBW technology. However, ultra-precision EBW equipment has been developed early on the other field, which prepares itself for future development.

2.2.1 Developmental history and applied tendencies

EBW was created in 1950's and used in nuclear industry. Because it could be achieved the highest precision in position and formed the highest depth-to-width ratio of weld, it could
also be applied, undoubtedly, in the industry of aerospace and national defense [51]. In the early stage of EBW development, its equipments which required high vacuum level were not used extensively because of the high cost and low productivity. Subsequently, low and non-vacuum systems were developed to greatly reduce the working time, these equipments were finally accepted widely [30,52].

On the other hand, studies on the electron microscope have been conducted since K. H. Steigerwald used electron beams to work with materials in 1948 [51]. In 1965, England Cambridge Company first developed the commercial SEM, which was primarily used for observing material surfaces. Linked with an energy dispersive spectrometer (EDS) or wavelength dispersive spectrometer, a SEM can further analyze the chemical compositions of materials. SEM has constantly improved image resolution under high magnification, and is considered the most important inspection equipment for analyzing materials. The inner structure and operating principles of SEM are very similar to those of EBW, except that the former is much smaller than the latter in terms of electron beam energy, workpiece dimensions, and spot and equipment size.

In 2001, F. Banhart first successfully soldered 15nm-diametral carbon nanotubes with field emission SEM [53] and created the new era of welding history. Thereafter, EBW researches about carbon nanotubes were published continuously [54,55]. This demonstration would be good for the research and development of ultra precision integrated circuit in the future.

2.2.2 Classification of electron beam welding system

Extensive research and development has made EBW applicable to numerous situations – even the space environment [56]. The following section describes the characteristics of various systems.

(1) Classified by accelerating voltage

An accelerating voltage provides the dynamic energy of electrons, and determines the fusion penetration depth in the workpiece. This voltage can be divided at 60 kV into two types,
which require different amounts of radiation protection [30,51].

(a) *Low-voltage system*. Output voltage and operating power are below 60kV and 60kW, respectively. Compared with a HV system, a LV system is more convenient for welding process because its electron gun can move freely. Meanwhile, it is simpler in construction, requires less maintenance, and can be used on thinner workpieces. The maximal depth-to width ratio can reach 12:1.

(b) *High-voltage system*. This type of system has an accelerating voltage and maximal power above 60kV and 100kW, respectively. High accelerating voltage and output power are good for increasing working distance and penetration effect, so the electron gun tends to be designed in the fixed mode. This system is applicable to welding thick workpieces, and its depth-to-width ratio can reach 25:1.

(2) **Classified by vacuum level**

The extent to which the electron beam is scattered has a direct influence on the welding efficiency and is dependent on the vacuum level. EBW equipment can be divided into non-, low-, and high-vacuum EBW systems, with the division points at 25torr and $1 \times 10^{-3}$ torr [30,57].

(a) *High-vacuum system*. To prevent the electron beam from inducing serious scattering, low energy density, and positioning deflection, the high-vacuum level in the working chamber should be kept above $1 \times 10^{-3}$torr. This level can produce the maximal weld depth-to-width ratio, welding precision, and working distance, but it also wastes more time and reduces production efficiency.

(b) *Low-vacuum system*. This type of system was developed immediately after the improved performance of electron gun. It often maintains between $1 \times 10^{-3}$torr and 25torr, and wastes less time than the high-vacuum system. It is applicable for mass volume production, but is unsuitable for active metals such as titanium and magnesium. Also, it reduces the weld depth-to-width ratio and welding precision.
(c) Non-vacuum system. To avoid rapidly oxidizing the filament, the electron gun in this system still maintains a high vacuum. System operators must be specially shielded from potential radiation. When the workpiece is located in the open atmosphere, however, the beam dispersion generates a significantly lower energy density and weld depth-to-width ratio. Thus, the working distance decreases between 20 to 50mm [11,58-60]. This type of system is suitable for welding thin workpieces [5].

(3) Classified by input energy [61]

When the input energy mode changes from continuum to interim, input energy and welding efficiency also occurs variations. The following section describes the differences between these energy modes.

(a) Continuous electron beam welding system. This is currently the mainstream system. Compared with a pulsed EBW system, the continuous EBW system can form higher quality welds.

(b) Pulsed electron beam welding system. Along with the standard parameters for EBW, pulsed EBW possesses its own unique parameters that must be considered: pulse-on time, pulse-off time, pulse amplitude, and pulse shape. Because the cooling cycle can be performed during the pulse-off time during EBW, this system forms a narrower weld than the continuous EBW system. This system is therefore suitable for welding thin plates, and fines the weld grain. The disadvantage of pulsed systems is that they easily produce spatter and porosity, but frequency variations have no obvious influence on the depth of weld.

(4) Classified by welding precision

At present, EBW machines are used for welding micron- and nanometer-scale materials with an electron microscope [53-55]. Therefore, welding precision can be divided at 0.1mm into two types as follows.

(a) Traditional electron beam welding system. Before 2001, all EBW machines belonged
to this system, which is also called the sub-millimeter-scale EBW system. The maximal input energy can penetrate a 250mm-thick steel plate, and the minimal power is above 100W. Focal ability and image resolution limit welding to a 0.1mm-thick foil.

(b) *Precision electron beam welding system.* In 2001, German researcher F. Banhart used field emission SEM to successfully solder carbon nanotubes of 15 nm in diameter [53]. This equipment, currently in the research stage, can be called a nanometer-scale EBW system. The chief characteristics of the system are high image resolution, low energy input, short working time, and precision positioning and adjusting, which meet the welding requirements for micron- or nanometer-scale components. Its beam power is limited below several kW. For this equipment to become a commodity, problems in temperature measurement, image processing integration, clamping, and fixing must be resolved. In the future, this technique may be used widely for micromechanical electronic and nanometer fields. Some researchers are presently using computer simulations for auxiliary analysis [54]. Figure 2 plots the relationship between SEM and EBW equipment.

### 2.2.3 Principles of electron beam welding

An EBW machine consists of a working chamber, an electron gun, a power supply system, a vacuum pump system, and a control system. The filament of the electron gun

![Figure 2](image_url)  
**Figure 2** Equipment modification for SEM and EBW.
provides many free electrons by thermal emission so as to form an electron cloud, and a superfluous of electrons pass through the anode at 30–70% of the velocity of light to reduce the density of the electron cloud. Because the electron beam diverges during propagation, it needs to be focused again to achieve sufficient power density [5] (A standard coil provides 7° deflection at maximum [62]). When the beam impinges on the surface of the workpiece, 95% of its kinetic energy is transformed into thermal energy, and the resulting power density can be as high as $10^7 \text{W/mm}^2$, which can be used for welding a metal workpiece [6,51,63]. Its temperature for fusing metals can reach 6000K [64]. The inner structure of electron gun is shown in Figure 3.

![General arrangement of electron gun](image)

Figure 3  General arrangement of electron gun [62].
Many parameters must be set by computer to satisfy EBW precision requirements [30]. Weldment quality is primarily affected by six parameters [5,6,30,51,59,60,65,66] as follows.

(1) *Accelerating voltage* (*V*, kV)

This item controls the velocity of the electrons, which use voltages between 15 and 200kV [30]. By increasing the accelerating voltage, the scattering effect of the electron beam caused by material evaporation can be reduced. The fusion depth of the weld, the input energy, the energy transfer efficiency, and the depth-to-width ratio of EBW can be increased as well [64,65].

(2) *Beam current* (*I*, mA)

This is also known as the welding current, and ranges between 25 and 1000mA [30], but the lower current (3mA) can be used for seam tracking [62]. The beam current determines the number of electrons that impinge on the surface of the workpiece. The width and depth of weld, the input energy, and the transfer efficiency of EBW can be increased by increasing the beam current [13,64,65]. For this parameter to be controlled accurately, the filament current should reach saturation point before welding in order to avoid unexpected results [60].

(3) *Welding speed* (*υ*, mm/s)

The welding speed is the relative speed between the electron beam and the workpiece; the movable device can be either the electron gun or the gripper. In the EBW process, faster travel causes a higher pore density [5], a narrower keyhole and weld [13,67]. At the same time, it also leads to a shallower depth of the weld, less grain growth, less heat transfer into the base material, and greatly reduced distortion [51,64,65].

(4) *Focused beam spot size* (*ψ*, mm)

This provides an effective way to quantify the focal position. A diameter of 0.1–1.0 mm is typical for EBW [51]; it depends upon the focal current, the beam power, and the working distance. A higher energy density of the electron beam can be generated on the surface of the workpiece with a smaller spot size and a narrower weld [65] at constant power.
consumption. When the focal position is close to the workpiece bottom, the penetration depth becomes larger [30,68]. At this time, the beam defocuses on the workpiece surface, so the weld width becomes wider again [13,58,64]. In large convergence angles, the penetration depth is greater for an underfocused weld than for an overfocused weld [69]. The Arata beam test (AB test) is the most commonly used method in the industry to determine the focal position and the electron beam aperture. This method welds a comb-shape test piece inclined at a 30° angle along the welding direction, which depends on weld shape [59], as Figure 4 indicates.

(5) *Working distance* (mm)

The working distance is the distance from the focus coil to the workpiece, usually ranging from 25 to 150mm. The depth-to-width ratio of the weld increases as the working distance increases [69], but electron beam energy will be decreased to make weld depth shallower.

(6) *Vacuum level* (torr)

Vacuum effects on the EBW process can not only reduce beam scattering, but also help prevent arcing and glow discharge problems resulting from contamination by oxygen,
hydrogen, and other elements [62]. The weld penetration depth becomes shallower below $7.5 \times 10^{-3}$ torr [51]. Section 2.2.2 discusses this aspect of EBW in further detail.

Whether or not the EBW parameters match each other, the results will influence the weld width, penetration depth, and heat transfer efficiency [65]. In other words, whether or not the EBW power density forms a symmetrical Gaussian distribution, it can directly affect the weld appearance [70]. An electron beam with distorted power density has difficulty forming a sound weld, and also induces weld defects. Industry technicians use the “DIABEAM” beam diagnosis system to measure the power density distribution of the electron beam. This method uses electron beam scan over a 25µm-wide slit (for multi-pass) or a 20µm-diametric pinhole (for single pass) diaphragms, and a computer integrates all the data into a three-dimensional energy distribution image [59,60].

The optimal parameter design is important for the successful application of EBW processes [66] and the total input energy can be calculated by the parameter data. The EBW equipment is commonly operated in a high vacuum, so the loss of electron energy due to scattering is very small. Accordingly, the input energy ($E_e$, J) of EBW can be expressed as [64]

$$E_e = \frac{\eta^*}{4.2} \frac{V I \phi}{\nu} = \frac{\eta^*}{4.2} \frac{P \phi}{\nu}$$  \hspace{1cm} (2-1)

where $\eta^*$ is the transfer efficiency and $P$ is the total output power (W) of the electron beam.

The transfer efficiency of EBW energy, while generally the highest among all welding techniques, is still not 100% because some of the input energy goes to heating material in the zone adjacent to the weld and overheating and evaporating liquid metal in the FZ [51]. Whether or not the weldment undergoes complete fusion penetration will therefore depend on the thermal transfer efficiency ($\eta_t$) of the EBW [65,68,71]:

$$\eta_t = \frac{P_f}{P_e} = \frac{\nu AH}{P_e}$$  \hspace{1cm} (2-2)

$$P_e = P \eta_e$$  \hspace{1cm} (2-3)

$$H = C(T_m - T_0) + H_f$$  \hspace{1cm} (2-4)
In the above formulas, $\eta_e$ is a coefficient taking into account the energy dissipated by backscattered electrons, $P_f$ the effective beam power, $P_e$ the input power, $A$ the cross-sectional area of the melting zone, $H$ the heat content, $C$ the mean specific heat from room temperature to melting temperature ($T_0, T_m$), and $H_f$ is the heat of fusion.

If no thermal conduction loss takes place in the metal, the ideal penetration depth ($p_i$) is as follows [64].

$$p_i = \frac{1}{2.1 \nu \varphi} \frac{1}{(C \rho T_m + H_f)}$$

$$\alpha = \frac{k}{C \rho}$$

(2-5)

(2-6)

where $\rho$ is the material density, $k$ is the thermal conductivity, and $\alpha$ is the thermal diffusibility.

In the formula above, the weld penetration depth increases in direct proportion to the input energy, and the right third part represents the fusibility of the material. In other words, when the different materials are welded under the same parameter conditions, the weld penetration depth depends on the fusibility of the material. Therefore, the material melting point, thermal conductivity, and diffusibility are all key factors in the penetration depth.

2.3 Fusion Welding Metallurgy for Electron Beam Welding

Generally, there are three ways in which parts may be fastened together [72].

(1) Mechanical fastening process

This is the well-known bolting and riveting method. Joining strength depends on the strength of the bolt (or rivet) and the base metal, but there are some problems (such as SC, crevice, and galvanic corrosion) in the assembly. Splicing with mechanical fastening adds the additional weight and volume, increasing material cost and production waste. Further, this method is not suitable for lightweight considerations.

(2) Gluing process

Adhesion is the most prevalent and economical joining method for small-loading
situations in daily life. The success of this method strongly depends on surface structure and
 glue composition. Though the intermediate glue layer effectively prevents contact corrosion
 [73], its use is often limited by temperature. Therefore, gluing cannot satisfy most engineering
 requirements.

(3) Welding process

This process uses enough energy to break the interatomic bonds of the local material,
 and then reforms new bonds to join materials together. Welding parameters must be adjusted
 properly according to the metallurgical properties of various materials. If the relationships
 between metallurgy variation and control parameters can be understood completely, it is
 relative easy to produce an optimal weldment.

2.3.1 Relationships between casting and fusion welding

From the process viewpoint, casting and fusion welding are similar processes for
 melting and solidifying materials in a specific environment. Casting shapes a product by
 withdrawing a cast from a die, while fusion welding combines bother materials into one.
 Many similar skills can be used in both processes to obtain high quality products.

For input energy analysis, there are three geometrical forms of heat source: a point
 source, a line source, and a plane source. The penetrating source of EBW is usually discussed
 in terms of a line heat source. The radiative and convective losses of EBW are therefore
 usually small, but thermal conductivity contributes most to temperature distribution [74].
 When the heat input increases during the course of penetration, welding turns into mere
 cutting [75].

When a material with good heat conductivity is welded, the crystals that form during
 weld solidification are nucleated by epitaxial growth at the solid-liquid interface. In the weld
 pool, the solidification velocity \( R \) is very close to the welding speed \( \nu \), and the relationship
 [72] can be defined as

\[
R = \nu \sin \tau
\]  

(2-7)
where \( \tau \) is the angle between the tangent to the weld pool boundary and the welding direction. If \( T, t, \) and \( x \) represent the temperature, time, and distance, respectively, the temperature gradient \( (G) \) is

\[
G = \frac{\partial T}{\partial x} = \frac{\partial T}{\partial t} \frac{\partial t}{\partial x} = \frac{\partial T}{\partial t} / \frac{\partial t}{\partial t} = \frac{1}{\nu} \frac{\partial T}{\partial t} \quad (2-8)
\]

For a three-dimensional heat flow, the temperature gradient from the heat source to the rear of the weld pool \( (x_r) \) and the \( G/R \) ratio can be derived as follows.

\[
\frac{\partial T}{\partial t} = \nu \cdot \frac{T_m}{x_r} \\
G = \frac{T_m}{x, \nu \sin \tau} = \frac{T_m}{x, \nu} \quad (as \ \sin \tau = 1) \quad (2-10)
\]

Overall, the grain structure of the weld depends on the \( G/R \) ratio, solute content, and the shape of the weld pool. As the fusion boundary moves forward, grains continue to grow in a columnar fashion. A primary grain structure can be determined by growth competition and the \( G/R \) ratio, and the grain size decreases as the \( G/R \) ratio decreases, as Figure 5 indicates. Micro-segregation within grain, which results from solute content, forms the substructure. Additionally, the distance between the heat source and the downstream edge of the weld pool increases as the welding speed increases. Because solidification parameters decrease, the weld tends to form equiaxial grain. On the other hand, the grain size in the FZ is also affected by the equiaxial mechanism of the HAZ. To further fine grain, ultrasonic vibration, electromagnetic oscillation, and impulse beam are all relatively effective methods [72].

Figure 5  Factors controlling the growth mode during solidification [72].
For most fusion welding processes, metal mixing in the weld pool is generally uniform unless the butting materials are significantly different. However, gases are very easily sucked into the weld to form pores during solidification. From the casting process viewpoint, there are three causes of porosity in die-casting workpieces [13].

(1) During melting material flow, air (or shielding gas) can mix into the material.

(2) During solidification, pores nucleate and grow as solubility decreases.

(3) During solidification, volume contraction forms shrink holes (linear and volume contractility is 1.7% and 5.0%, respectively [1]).

When an electron beam impinges on the surface of a material, fusion welding mode changes over from heat conduction to keyhole. Because the keyhole mode has a higher energy density, it causes the central part of the weld pool to reach a boiling point. Two other reasons for pore formation are as follows.

(1) Elements with high vapor pressure are volatilized quickly.

(2) Oxide and nitride are dissolved and precipitated again [72].

Defects (such as pores, cracks, inclusion, etc.) appearing in the casting process can also appear in the welding process. Because the top and bottom of the weld pool is not in a closed state, this situation produces complex changes in the appearance of the weld.

2.3.2 Various force effects in the weld pool

EBW parameter combinations not only directly influence the input energy distribution, but also change the weld pool flow. These parameters are key factors in forming a sound weld [59,70]. The principle is that EBW focuses electrons at a high speed, impacting the work piece. This collision immediately transforms kinetic energy into thermal energy, and then forms a keyhole containing melting and evaporating material by a high power density (>4.5×10^3 W/mm^2) [72]. As the electron beam moves forward, the melting and evaporating material flows around to the rear of the keyhole. This process forms a weld with high depth-to-width ratio using the interaction between high energy density and local vapor
pressure [67], as Figure 6 indicates (the solid and dash arrows indicate the force and flow directions, respectively). During solidification, the weld appearance depends on five different forces interacting in the weld.

(1) *Electron beam impact force* ($F_1$)

Power and focal position determine the force of an electron beam [51]. Excessive impact force may change the flow and induce undercut and hump. These problems can be amended by tilting the electrode angle to reduce the influence [72].

(2) *Electromagnetic force* ($F_2$)

This force always coexists with the electron beam impact force. The electromagnetic force is derived from the beam current, which tends to produce an inwardly directed (conver-
gent) convection in the weld pool. Its effect is not apparent when using small current [72,75].

(3) **Repulsive force of the evaporating material** ($F_{3H}$ and $F_{3V}$)

This force is the main source of shear force in EBW, and tends to cause divergent convection that pushes the melting metal behind the electron beam, and concurrently keeps the melting metal from falling back into the keyhole. Analyzing the influence of this force can be done by calculating its two components [75].

(4) **Surface tension force**

Figure 7 illustrates how surface tension force plays an important role in interfaces between different phases in the weld pool. If a liquid drop (A) stays at equilibrium on a plane surface (B), the Young-Dupré equation may be defined as [72]

$$\gamma_{S/V} - \gamma_{S/L} = \gamma_{L/V} \cos \theta$$  \hspace{1cm} (2-11)

When $\gamma_{S/V}$ is greater than the sum of the other two terms, the contact angle is zero and the liquid will spread laterally. Apparently, the wettability of a material is affected by this force, and the flow velocity ($v_f$) can be expressed by the Poiseulle formula as follows [72].

$$v_f = \frac{\gamma_{L/V} \cos \theta \cdot d}{4\eta \cdot h}$$ \hspace{1cm} (2-12)

where $\theta$ is the contact angle, $d$ is the distance between two parallel separated plates, $\eta$ is the viscosity, and $h$ is the height to which the liquid rises.

![Figure 7 Sessile drops. (a) $\theta>90^\circ$: drop will not enter a capillary gap. (b) $\theta<90^\circ$: drop will enter and fill a capillary gap [72].](image)
Temperature distribution decreases radiantly \((dT/dx<0)\) during welding, so a melting material with high surface tension can stabilize the weld surface. To produce a superior quality weld, three factors should be considered.

(a) *Alloying elements.* The surface tension of melting materials often depends on alloying elements, even surfactants. A melting material with a low surface tension easily forms undercut and crowning.

(b) *Weld pool temperature.* Higher temperatures zone often cause a lower surface tension force in the weld pool \((i.e. \, d\gamma/dT<0)\). This phenomenon causes the outward shear force \((i.e. \, d\gamma/dx>0)\) on the surface, forming a divergent convection, as Figure 8(a) indicates. Therefore, the weld exhibits a small depth-to-width ratio [72].

(c) *Selecting filler metal.* When a filler with surfactant is used, the surface tension force decreases radially \((i.e., \, d\gamma/dT>0)\), because surfactant concentration is lower at higher temperatures) to produce an inward shear force \((i.e., \, d\gamma/dx<0)\) on the surface, as Figure 8(b) shows. This phenomenon causes the convergent convention, so the weld has a high depth-to-width ratio [16,72]. In DMW, the migration of trace elements also causes a similar effect.

Flow that is caused by a surface tension gradient is called Marangoni’s flow (also called thermo-capillary convention) [76]. When dissimilar materials are welded, the weldment strength, weld width, penetration depth, and thermal transfer efficiency can be changed by the same EBW parameters [65].

![Figure 8](image_url)  Maragoni’s flow in a weld pool: (a) divergent flow, and (b) convergent flow [72].
Gravity has a beneficial effect on flat welding because it helps produce a smooth weld surface, but it tends to displace or distort a weld bead in vertical positions. A welder usually uses the arc force to counter the pull of gravity on the bead. Gravity affects the static force of vapor \( F_{4V} \) and the reflowing force of the melting material \( F_5 \) \([72]\).

According to theory derivation and experimental results \([75]\), the relationship between these forces can be expressed as \( F_{3H} \approx F_{3V} \) (about 400mg) \( \gg F_5 \) (250mg) \( \gg \gamma \approx F_{4V} \) (about 25mg) \( > F_{4H} \approx F_1 \) (3mg) \( \gg F_2 \) (4 \times 10^{-5} mg). The downward pressing forces include \( F_1, F_2, F_{3V}, F_{4V}, \) and the backward pushing forces are \( F_{3H}, F_{4H}, \) and \( \gamma \). These forces and \( F_5 \) together determine the weld shape. Besides this, periodic oscillation resulting from focusing system \([59]\) can induce capillary waves on the weld surface and at the weld root. This becomes more apparent when at lower frequencies \([74]\). The regular oscillating beam and irregular surface fluctuation frequencies \([72]\) should be balanced to further improve weld quality.

Using a computer-controlled EBW machine is helpful for understanding each parameter effect, and welding a material with high thermal conductivity under a high vacuum greatly can reduce many harmful influences such as oxidation and HAZ. Further, parameter characteristics are easily revealed from superior fluidity and high vapor pressure as welding a material with a low melting and boiling point. Based on these factors, magnesium alloys (vapor without toxicity) are the best choice among all engineering materials.

### 2.3.3 Characteristics of dissimilar metal welding

In recent years, cutthroat competition has led manufacturers to heighten process efficiency and use more lightweight alloys. DMW is thus important to modern manufacturing, which provides flexible design to use for both technical and economic considerations. DMW can be divided into two categories: (1) different major and minor compositions between butting materials; and (2) the same major composition but different minor composition. Compared with SMW, DMW possesses a more complex structure resulting from concentration gradient of chemical composition. Though the joints still produce a galvanic
effect as in SMW, the composition difference between butting materials is significantly less. This reduction minimizes the harmful influences of intermetallic compounds. Therefore, to improve weldment properties in DMW, minor differences in compositions are preferable to major compositions.

When performing DMW without filler, the fusion welding process is limited by the mutual solubility of the metals, the formation of brittle phases, high residual stresses arising from phase segregation and associated variations in the thermal expansibility, and other factors. These problems can be addressed by varying the welding parameters, component design, and service requirements [6], but the extent of improvement is very limited by conventional welding technology. According to previous research [20], traditional fusion welding (such as TIG welding) fails in butting pure Mg and Al alloys; the strength of the weldment is nearly zero. Some researchers believe that the formation of intermetallic compounds plays a key role in reducing the weld strength. Even in experiments where the brittle phase was prevented from forming by friction stir welding, however, the strength of weldment only reached 84 MPa [17-20]. Therefore, the question which has been touched from time to time should be discussed further.

Based on the considerations above, EBW and LBW with high energy density and welding precision can control the desirable fusion ratio of two metals by selecting a filler, adjusting the focal beam spot size, and deflecting to the material with high thermal conductivity or low melting point to significantly reduce the formation of intermetallic compounds [6,51]. These methods cannot completely avoid the problems of DMW, but they can minimize its harmful effects.

Table 7 represents the weldability of butting various metals via EBW without filler, which is classified on five levels and established by the American Welding Society according to metallurgical compatibility and other factors [77]. On the other hand, AZ61A, AZ92A, and AZ101A can be used as fillers when welding AZ-series alloys. AZ61A and AZ101A are useful for forging and casting alloys, respectively, and AZ92A can be used for both. These fillers may reduce the probability of cold and hot cracking. If no filler is available, most base metals
may be welded with strips cut from the base metal [78].

### 2.3.4 Formation of weld defects

Some of the usual defects incurred when welding materials by EBW, and their ameliorative actions, are discussed below.

#### (1) Heat-affected zone

No weldment can avoid forming a HAZ, which is often classified into two regions: the high temperature region (where grain growth takes place) and the low temperature region (where precipitation may occur). Compared with casting materials, the negative effect of the HAZ is more significant for forging materials [72]. The HAZ width serves as an indicator of the input energy level. Therefore, a welding process with low heat input, high energy density,

| Base metal | Ag | Al | Au | Be | Co | Cu | Fe | Mg | Mo | Nb | Ni | Pt | Re | Sn | Ta | Ti | W |
|------------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Al         | 2  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Au         | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Be         | 5  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Co         | 3  | 5  |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Cu         | 2  | 2  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Fe         | 3  | 5  | 2  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Mg         | 5  |    | 2  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Mo         | 3  | 5  | 2  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Nb         | 4  | 5  | 4  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Ni         | 2  | 5  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Pt         | 2  | 5  | 1  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Re         | 3  | 4  | 4  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Sn         | 2  | 2  | 5  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Ta         | 5  | 5  | 4  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Ti         | 2  | 5  | 5  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| W          | 3  | 5  | 4  |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Zr         | 5  | 5  | 5  |    |    |    |    |    |    |    |    |    |    |    |    |    |

Note: 1. Very desirable (solid solubility in all combinations), 2. Probably acceptable (complex structures may exist), 3. Use with caution (insufficient data for proper evaluation), 4. Use with extreme caution (no data available), and 5. Undesirable combinations (intermediate compounds formed).
and high heat efficiency can help avoid some of the negative influences of the HAZ [79]. Once welded by arc welding in the thermal conduction mode (with an energy density below $4.5 \times 10^2 \text{W/mm}^2$) [59], the weld becomes wider and shallower, and the negative effects of the HAZ become more significant [30].

(2) Cracks

Segregation and cycling heat stress are the main causes of weld cracking. Weld cracks can be divided into two types, according to the way they form.

(a) **Hot cracking**. When the grain boundary forms a liquid eutectic film or precipitates impurities with low bonding force, liquation or solidification cracking will occur in the intergranular mode, which results from residual stress during weld thermal cycles [80]. The cracks tend to disappear if they are refilled with surrounding low melting point eutectic material [81]. For AZ-series alloys, solidification cracking starts to develop when the chemical composition promotes a wide freezing range, which typically occurs above 6wt.% Al and 1wt.% Zn (as in AZ63A and AZ92A) [21,32]. This defect can be evaded by fine grain, low welding energy, or using filler [72].

(b) **Cold cracking**. Cold cracking is a transgranular fracture which occurs mainly in hard locations during solidification. This is because the different phases in the weld have different thermal expansibilities, which cause irregular distributions of thermal stress and lead to cracking. Prewelding and postwelding heat treatments can ameliorate this situation.

(3) Pore or cavity

Gases (such as hydrogen) originally existing in the weld pool tends to escape rapidly during cooling. When gases cannot be expelled before solidification, they form weld pores in the weld [82]. Additionally, if a material with numerous pores is welded, the original pores form larger pores by combining with each other [83]. EBW causes a very high metal vapor pressure in the keyhole. Sometimes the pores cannot expel in time because the vapor is volatile enough to rapidly decrease the temperature on the keyhole surface and increase the
viscosity in the weld pool [68]. For instance, the temperature can decrease as much as 300K, even though Al alloys only contain 0.1wt.%Zn [69]. Oily substances can also be dissolved to reform pores in the weld after solidification [63]. This situation is more serious when welding thicker materials with low melting points [10,84]. Moreover, unsuitable parameters [14] and shielding gases can easily cause turbulence [4] that trap gas in the weld and form large, irregular cavities [61]. Effective ways to decrease these kinds of defects include cleaning the workpiece surface, increasing dovetailing precision, selecting the forging material, adding a proper filler [9], reducing the cooling rate [72], lowering the welding speed, using a defocused beam, oscillation beam, or performing multi-pass welding [51,83].

(4) Imperfect shape

Defects often form in the following four ways, in order of their probability.

(a) Irregular surface. This defect results from a cavity collapse in the weld pool, which causes a spiking phenomena in the appearance of the weld after it solidifies [61]. Highly volatile elements (such as Mg and Zn) [9] and an excessive input energy [23] also form irregular cavities in the weld.

(b) Root concavity. This situation occurs when there is insufficient input energy and beam current [51]. It can also possibly occur from refilling cavities or solidifying shrinkage during weld solidification [61].

(c) Undercut. When higher beam current and accelerating voltage are used for welding a thick workpiece, defects form easily because the electron beam impact force increases greatly. Fabricating a groove, decreasing the welding speed [51], or using a filler metal can help avoid this problem [9].

(d) Crowning. When materials with numerous pores are welded, a sudden expansion of the gases inside can cause a bulgy weld crest, which may even overflow the workpiece surface [85]. This situation can be improved by decreasing the input energy [83]. Additionally, some believe that weld crowning increases greatly when the welding speed is too high to match the focal position [4]. This is especially significant for high
power electron beams [86]. Fabricating a groove and decreasing the welding speed can help ameliorate this problem [51].

(5) Spatter

When a material with low surface tension is welded by an oscillating beam or with an excessive energy density, spatter is formed easily [10,16,23]. Using a defocused beam [13,64,72] or reducing pores, O, and N contents in the material [5] can effectively lower spatter formation.

(6) Lack of fusion

Sometimes the weld with high depth-to-width ratio is overlooked easily that with inexact positioning of the electron beam with respect to the abutting faces to be welded. This problem can be amended by training the operator and installing a seam tracking system.

2.4 Welding Technologies for Mg-Al-Based Alloys

Because it is limited by high chemical activity and poor formability, the selection of a welding process for magnesium alloys is very important. Otherwise, weld defects will greatly decrease the weldment strength, which results from high notch sensitivity [22,87]. The following section discusses the characteristics and various welding technologies of Mg-Al-based alloys necessary in order to accurately select a suitable welding process.

2.4.1 Characteristics of Mg-Al-based weldment

Almost all magnesium alloys can be joined by welding [1] and superior weldment properties will be obtained with filler [78]. For fusion welding without filler, hot cracking [88] easily occurs in weldments for die-casting magnesium alloys and reduces its strength, this results from the long temperature interval of the semisolid state. Welds in forged magnesium alloys occasionally contain few cold shuts, but its strength is still better than that of die-cast magnesium alloys which has many pores connected to each other that form serious defects in the welds [13]. Also, the influences of high chemical activity and evaporative loss are
incapable of being neglected. At this time, precision welding technique will be more suitable for jointing magnesium alloys than conventional technology. Table 8 represents the comparison between the weldabilities of various magnesium alloys.

Though they use the same welding parameters, various magnesium alloys exhibit different welding performance due to their different thermal physical properties. The following are two random examples: die cast AZ91D has a lower thermal conductivity of 51W/m·K than 139W/m·K for wrought AZ21A, so the former has a greater weld depth and volume than the latter [4]. Adding aluminum as an alloy up to 11.5wt.% also improves weldability since it tends to fine the grain structure [32]. However, it is sensitive to stress corrosion above 1.5wt.%, which should perform stress relief to amend weldment quality [1,30]. High-Zn alloys (>4wt.%) are not recommended for arc welding due to their tendency to crack [4,30]. On the other hand, magnesium contains a small amount of Th, possesses excellent welding qualities, and is relatively free from cracking [30,72].

Table 8  Relative weldability for various magnesium alloys [1].

<table>
<thead>
<tr>
<th>Casting alloy</th>
<th>Class</th>
<th>Forging alloy</th>
<th>Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM100A</td>
<td>B⁺</td>
<td>AZ10A</td>
<td>A</td>
</tr>
<tr>
<td>AZ63A</td>
<td>C</td>
<td>AZ31B</td>
<td>A</td>
</tr>
<tr>
<td>AZ81A</td>
<td>B⁺</td>
<td>AZ31C</td>
<td>A</td>
</tr>
<tr>
<td>AZ91C</td>
<td>B⁺</td>
<td>AZ61A</td>
<td>B</td>
</tr>
<tr>
<td>AZ92A</td>
<td>B</td>
<td>AZ80A</td>
<td>B</td>
</tr>
<tr>
<td>EK30A</td>
<td>B</td>
<td>M1A</td>
<td>A</td>
</tr>
<tr>
<td>EK41A</td>
<td>B</td>
<td>ZE10A</td>
<td>A</td>
</tr>
<tr>
<td>EQ21</td>
<td>B</td>
<td>ZK21A</td>
<td>B</td>
</tr>
<tr>
<td>EZ33A</td>
<td>A</td>
<td>ZK60A</td>
<td>D</td>
</tr>
<tr>
<td>K1A</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QE22A</td>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EZ41A</td>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WE43</td>
<td>B⁻</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WE54</td>
<td>B⁻</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZC63</td>
<td>B⁻</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZK51A</td>
<td>D</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZK61A</td>
<td>D</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: A, excellent; B, good; C, fair; D, limited weldability.
2.4.2 Traditional welding technique for Mg-Al-based alloys

Traditional welding of magnesium alloys requires high power under flux, shielding gas, or vacuum environment due to high chemical activity and thermal conduction. Not only the grains are coarsened, but many cavities and cracks form in the widening FZ or HAZ [1,88]. The strength of a joint is lowered in base metal, in work-hardened conditions, and as a result of recrystallization and grain growth in the HAZ [63]. The base metal (and fixture, if used) should therefore be preheated or stress relieved to address these problems [30]. The following section describes some traditional welding methods of Mg-Al-based alloys and their characteristics.

(1) Gas tungsten arc welding

TIG welding was created in the 1930’s [30], which used extensively for joining magnesium alloys and aluminum alloys [4,11]. This process must use a high input energy to weld metals with high thermal conductivity because its arc efficiency is only 66%. Thus treating, the HAZ and its grains of these weldments are easily widened and coarsened, respectively. For example, when welding 4mm-thick magnesium plates, the width of the HAZ is greater than 3mm and its grain size is between 50–70µm [16]. Additionally, the grain boundary contains many γ phase precipitates [73,79]. These problems can be improved by increasing the welding speed and cooling rate. This process is recommended for welding thin materials [30] and repairing cast defects [9].

Direct current electrode negative is seldom used on magnesium alloys because the arc lacks a cathodic-cleaning action to immediately remove the surface oxide layer. Therefore, the alternating current or direct current electrode positive helps produce a high quality weldment. The shielding gas is normally high purity argon. However, a mixed gas (75%He+25%Ar) is used for thicker materials (<4.8mm). For heavy thickness (>4.8mm), 100% He can be used to create a deep penetration [1,30,85,89]. For the best results, the electrode should be held close to the workpiece to produce an arc about 0.8mm [1]. The excessive welding current easily induces cold cracks in the weld, and an insufficient welding current can cause cold laps, porosity, and non-penetrating weld. The length of hot cracks can be shortened by carefully
matching the welding current with decreasing welding speed [90].

(2) Gas metal arc welding

Gas metal arc welding (GMAW) is also called MIG welding. Some researchers consider MIG welding to be less efficient than TIG welding [1], but others believe that its 85% arc efficiency makes it useful for welding thick materials [30]. The selection of the current mode, equipment style, and shielding gas for MIG welding is similar to TIG welding, but MIG welding uses a consumable electrode. Generally, a spray transfer should be used on thicker metal (>4.8mm) and a short circuit transfer used on thinner metal (<4.8mm), but globular transfer is not suitable [30,73,78].

(3) Friction stir welding

Friction stir welding belongs to a group of pressure welding methods, and is a solid-state joining process. The UK Welding Institute developed friction stir welding in 1991 [91]. The friction is generated by the relative motion between rotating components to produce heat for welding. Compared with fusion welding, this process can produce weldment with better mechanical properties, fewer intermetallic compounds, and no solidification cracking and residual pores. Not only are its requirements cheaper, but it is easy to train a welder in this method [19]. For instance, when extruded AZ31 alloy was welded by this process at 400°C, the fine grain weld surface structure had a similar hardness with the HAZ and base material. The weldment strength increases as friction time increases [7], but it is not quite as strong as the base metal [92]. Because the DMW process still forms some intermetallic compounds by diffusion, the weldment strength mainly results from mechanical interlocking at the irregular seam. To butt Mg-Al weldments, the joint efficiency is around 77%. The elongation, however, is as low as 4% [17,19,20].

(4) Diffusion welding

Diffusion welding is a solid-state joining process in which two clean metallic surfaces are come into contact at elevated temperatures (<0.7Tm) under low pressure. This technique permits the production of high-quality joints with little or no need for post-weld machining
Though this process reduces fabrication costs, the excessive processing temperature can decrease the life of the metal die, accelerate surface oxidation, and coarsen the grains. The weldment strength is low when forming intermetallic compounds such as β and γ phases at the interface in Mg-Al DMW, which necessitates careful consideration of parameters. This process can be matched with superplastic forming to produce superior quality weldment [8,38,93].

(5) Other welding methods

Resistance welding, flash welding, plasma welding, soldering welding, and brazing welding can also be used for welding magnesium alloys [30]. The chance of causing an accident can be minimized provided that safety measures are observed. Because their welding quality is poor, these methods are seldom used in industry [11].

2.4.3 Precision welding technique for Mg-Al-based alloys

Precision welding technology is also called high-energy-density beam welding [59], which can eliminate the aforementioned shortcomings with its low input energy, narrow HAZ, high welding precision, and depth-to-width ratio [4,11]. The weld structure with fine crystal can be formed by fast cooling resulting from high thermal conduction, and its high Al content can produce brittle precipitates [5,9]. Studies on precise magnesium alloy welding to date concentrate on LBW [4,5,9-11,23,80,85,94-99] because of its convenience. However, LBW is limited by optical device tolerance for beam power, which restricts the degree of fusion penetration in thicker workpieces [58]. It is for this reason that EBW is the preferable choice. Both processes can be indicated in detail as follows.

(1) Electron beam welding

In general, magnesium alloys that can be arc welded can also be electron beam welded with the similar procedures [1]. Not only the alloys can decrease hydrogen content by high energy density as welded by EBW [13], but also create equiaxial grains with small diameters (<10µm) inside the FZ (which has no columnar grain) due to the low input energy and high cooling rate. Because melting magnesium alloys have a higher vapor pressure and greater
fluidity than other structural materials, the weld surface destabilizes easily. The grain size of the weld and the evaporation of the magnesium alloy can both be decreased by raising the welding speed, but this also causes many cavities to form in the weld root [5] and an uneven appearance on the weld surface. At this time, certain operating practices such as reducing the welding speed and using a slightly defocused beam can help to create sound welds [1,58]. When the Al content of a magnesium alloy is slightly increased, not only does the depth-to-width ratio of the weld increase but the weld surface becomes smoother (AZ-series alloy with higher Al content has greater energy-absorption efficiency to increase weld depth due to its lower thermal conductivity, which does not result from Marangoni’s flow). Ripples and spatters also become less distinct in such alloys [16]. In contrast, a high Zn content (above 1%) or excessive welding energy increases the vapor pressure and decreases the weld quality [1]. The above facts demonstrate that the process window (or parameter window) of magnesium alloys might be narrower than that of other engineering materials [5]. Imperfections in the functional parameters [16] and the addition of unsuitable elements caused by defects in the FZ can markedly affect the quality of the resulting weld.

(2) Laser beam welding

Since laser technology was developed in 1960, LBW has been used widely in welding field [30]. In setting parameters, weld appearance, and defect shape, it is very similar to EBW [4]. LBW can be divided into two types, which differ from each other in their laser generation and source: solid-state lasers (such as a Nd:YAG laser with a 1.06μm wavelength) and gas-lasers (such as a CO₂ laser with a 10.6μm wavelength). The wavelength difference has an apparent influence on the welding efficiency, depending on the absorption behavior of different materials [4,11,63,73]. Both lasers can be used regardless of vacuum, shielding gas, and atmospheric environment [58], but eye protection is necessary [30]. The shielding gas is normally argon for Nd:YAG lasers, but CO₂ lasers use a mixture of helium and argon. The purpose of mixing both gases is to reduce costs and control plasma, which gives the weld a high depth-to-width ratio. Thus, a gas flow of 12 l/min or higher is required for a satisfactory weld width [9,98,99]. If the FZ has a lot of pores, a filler can be used [5,9]. The optimal focal position of the laser on the workpiece surface varies from -1.2 to -2.0mm [9,97].
When a laser is focused on a smooth magnesium-made workpiece, most energy is reflected [4]. Previous research indicates that Nd:YAG lasers produce better welding effects than CO₂ lasers for magnesium alloys. This is because Nd:YAG lasers have a shorter wavelength, and can significantly reduce the amount of energy reflected before forming the key hole. Nd:YAG lasers not only form deeper welds, but they also reduce spatter. Thus, a Nd:YAG laser can produce a higher quality weld [23,98]. Additionally, other researchers also developed new processes to amend the problem of poor energy absorption. For example, the laser-TIG technique uses a laser beam placed on an axis with a TIG welding torch. Though this technique reduces the number of pores in the weld, the width in a previous study was too wide (an 8mm-wide weld was formed on a 5mm-thick plate) to retain the original precision of LBW [97]. There is room for improvement on this point.

2.5 Experimental Design for Engineering

In this study, three kinds of experimental designs will be adopted: COFAAT trend analysis, Taguchi robust design, and grey relational analysis. The merits and demerits of these analyses can be described as follows.

2.5.1 COFAAT trend analysis

COFAAT is a traditional method of analyzing stepwise the influence of each parameter in an instrumental inspection such as a tensile test. The tendency associated with each parameter can be found, and used to illustrate the experimental results when the points obtained by changing one parameter are linked together to form a curve in the plane. Therefore, not only can the change of bond strength for weldments be understood, but the optimum parameters can also be obtained. However, the cost is high and a long time is needed, and interactions between parameters are ignored.

2.5.2 Taguchi robust design

Taguchi Robust Design [100] also called Taguchi’s method and developed by Dr. Genichi Taguchi, which can be used to improve the quality of products and the
cost-effectiveness of a study. In this method, it is necessary to adopt a suitable orthogonal array to greatly reduce the number of experiments. The signal-to-noise (S/N) ratio $\eta$ (units dB) can be obtained after a series of calculations and is a barometer of the ability of a system (a process or product) to perform well in relation to the effect of noise. Generally speaking, a higher S/N ratio indicates better performance of the system and better stability of the product. Depending on the quality characteristics chosen, the S/N ratio can be calculated using a “higher-the-better” (HB), “lower-the-better” (LB), or “nominal-the-better” (NB) criterion, and is expressed as follows.

$$
HB: \eta = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \quad (2-13)
$$

$$
LB: \eta = -10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \quad (2-14)
$$

$$
NB: \eta = -10 \log \left( \frac{1}{n-1} \sum_{i=1}^{n} (y_i - \mu)^2 \right), \quad \mu = \frac{1}{n} \sum_{i=1}^{n} y_i \quad (2-15)
$$

where $y_n$ is an experimentally observed value, and $n$ is the number of experimental runs.

After the S/N ratios of all the experiments have been calculated by use of these formulas, a response table, a response graph, and a predicted optimum parameter are generated. An additional run at these settings of the response table or graph is required to confirm the reproducibility of the recommendation: if the predicted value approaches the experimental value (above 90%), the reproducibility is acceptable. Otherwise, the experiment should be replanned and reestimated. Thereafter, more sophisticated techniques using ANOVA can obtain contribution percentages from a more quantitative analysis to understand the influence of each parameter. The common applications of Taguchi’s method require all experimental runs in the orthogonal array before results can be obtained. However, in some situations, such as the exceeding of operational limits or the accidental breakdown of equipment, not all of the necessary data can be obtained, and estimates cannot therefore be made from the experimental results. So far, only one publication has dealt with this kind of problem [100]. The applicability of the method is still unknown, so it deserves more than passing notice.
2.5.3  Grey relational analysis

Dr. Julong Deng first proposed grey relational analysis in 1982, meeting the crucial mathematical criteria for dealing with poor, incomplete, and uncertain systems [101,102]. Grey relational analysis can be used to effectively solve the complicated interrelationships between multiple performance characteristics [95,96,103]. As its name implies, grey relational analysis exhibits infinite possibilities between black and white (or 1 and 0). Depending on the quality characteristics chosen, the measured data can be normalized (0≤xij≤1) using a HB, LB, or NB criterion. These criterions are expressed as follows.

\[
HB: \quad x_{ij} = \frac{y_{ij} - \min y_{ij}}{\max y_{ij} - \min y_{ij}} \quad (2-16)
\]

\[
LB: \quad x_{ij} = \frac{\max y_{ij} - y_{ij}}{\max y_{ij} - \min y_{ij}} \quad (2-17)
\]

\[
NB: \quad x_{ij} = 1 - \frac{\max \{\max_j y_{ij} - y_{ij}; y_{ij} - \min_j y_{ij}\}}{\max_j \max_j y_{ij} - \min_j y_{ij}} \quad (2-18)
\]

where \(y_{ij}\) is the original sequence for the \(i\)th experimental results in the \(j\)th performance characteristic, \(y\) is the assigned value, and \(\max y_{ij}\) and \(\min y_{ij}\) are the maximum and minimum values in the original sequence, respectively.

When \(x^0_i\) and \(x_{ij}\) are the reference sequence and the comparability sequence, respectively, the grey relational coefficient \(\gamma_{ij}\) can be defined as:

\[
\gamma_{ij} = \frac{\min \min_i |x^0_i - x_{ij}| + \zeta \max \max_i |x^0_i - x_{ij}|}{|x^0_i - x_{ij}| + \zeta \max \max_i |x^0_i - x_{ij}|} \quad (2-19)
\]

where \(\zeta\) is the distinguishing coefficient (0 ≤ \(\zeta\) ≤ 1) which can be adjusted in accordance with the actual condition. The average grey relational coefficient is the grey relational grade. Because each performance characteristic may influence the system differently, the grey relational grade (0 < \(\gamma^*_{ij}\) ≤ 1) can be modified by weights and expressed as:

\[
\gamma^*_{ij} = \sum_{i=1}^{n} \gamma_{ij} \omega_i \quad (2-20)
\]

The weight (\(\omega_i\), \(\sum \omega_i = 1\)) of each performance characteristic can be set using the
assigned method or entropy method. The latter is used when researchers cannot determine which performance characteristic is more important. Therefore, the entropy \( (E_i) \), relative weight \( (\lambda_i) \) and entropy weight \( (\omega_{ei}, \sum \omega_{ei} = 1) \) are defined as:

\[
E_j = \frac{1}{0.6487m} \sum_{j=1}^{m} W_j \left( \frac{x_{ij}}{\sum_{j=1}^{m} x_{ij}} \right) \tag{2-21}
\]

\[
W_j(x) = x e^{(1-x)} + (1-x) e^x - 1 \tag{2-22}
\]

\[
\lambda_i = \frac{(1 - E_i)}{n - \sum_{i=1}^{m} E_i} \tag{2-23}
\]

\[
\omega_{ei} = \frac{\lambda_i}{\sum_{i=1}^{m} \lambda_i} \tag{2-24}
\]

Taguchi’s method cannot handle problems with multiple performance characteristics such as the relationship between welding parameters and weld defects (e.g. undercut, root concavity, crack, cavity, and pore), so it must be paired with grey relational analysis to solve these problems in this study.