Reducing the Porosity in Die-Cast Magnesium Alloys during Laser Welding

Nearly pore-free and completely penetrated laser beam welds in die-cast magnesium alloys are obtained by selecting laser power density and careful control of heat input

BY J. ZHANG, J. G. SHAN, J. L. REN, AND P. WEN

ABSTRACT

Weld porosity is a severe problem during laser beam welding of magnesium alloys. In this paper, gas content in the base metal of high-pressure die-cast AM50 magnesium alloy is measured by inert gas fusion analysis, and the high gas content, 63.4 mL/100 g (mostly hydrogen), is found to attribute to the high weld porosity during laser welding. Furthermore, effects of welding parameters on weld porosity are investigated, and a porosity prevention technique is realized by appropriately selecting laser power density and careful control of heat input. The control strategy of this technique is that the selected laser power density should be greater than 1.8 × 10^6 W/cm^2 such that the variation of weld porosity with heat input minimizes at a moderate heat input value where complete joint penetration is also ensured; however, the power density should be less than 4.1 × 10^6 W/cm^2 to avoid poor weld surface quality. Sound welds with low porosity (<5%), complete joint penetration, and good surface quality are obtained through this prevention technique, and the tensile strengths and elongations of these welded joints are also comparable to the base metal.

Introduction

Applications for magnesium alloys have increased in a variety of fields, such as the aerospace industry, automobile manufacturers, and electron apparatus. These increases are attributed to the alloys’ low density, high strength-to-weight ratio, and high damping capacity. Among these magnesium products, die-cast magnesium alloys occupy ~80% of the applications (Refs. 1, 2). Despite their good casting qualities, die casting of large and complex components is not always practical or economically favorable. Therefore, welding, as a main joining method, plays an important role in applications of die-cast magnesium alloys, such as manufacturing of parts and repair of casting defects. Conventional gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) methods can cause several severe welding problems, such as weld pool collapse, liquation cracks, residual stresses, and distortion, whereas laser beam welding, being a high-energy-density welding method, can greatly relieve these problems (Refs. 1–5) and therefore is considered to be very efficient and promising.

For magnesium alloys (Refs. 5, 6), especially for die-cast alloys (Refs. 6–9), weld porosity was found to be a major concern during fusion welding, which greatly limits its practical application in industry. There are several factors that were considered to contribute to the high tendency of porosity in magnesium alloy welds: a) entrapment of gas (air) in the base metal due to surface turbulent flow during the manufacturing process (Refs. 2, 10, 11); b) rejection of dissolved hydrogen from solid phase to liquid phase during solidification (Refs. 2, 12, 13); and c) collapse of unstable keyholes (Refs. 14, 15) and entrapment of shielding gas (Refs. 11, 14). Keyhole instability in magnesium alloys was considered not to be a major factor (Ref. 6), yet the effects of entrapped gas in the die-cast base metal during the manufacturing process could be very profound, as demonstrated by the fact that die-cast magnesium alloys, which have higher gas content (Ref. 16) due to entrapment of gas during the high-pressure die-casting process, have a much higher porosity tendency (Refs. 2, 4–6, 10) compared to vacuum die-cast magnesium alloys (Refs. 17, 18) and their wrought counterparts (Refs. 7, 8, 16). The effects of gas entrapment include two aspects. First, without being dissolved, some of the entrapped gases can form micropores in base metal, leading to high initial porosity (area-percent porosity 2%~5%, Refs. 6, 10) and making heat treatment of them very difficult. Expansion and coalescence of these preexisting pores were considered to be a main cause of the increase in weld porosity during laser welding, proposed by Zhao and DebRoy (Ref. 6). Second, interaction of water vapor (H2O) contained in the entrapped gases with magnesium can generate hydrogen (Ref. 2), leading to a high hydrogen content in the base metal existing in both atomic and molecular forms. The high hydrogen content in die-cast magnesium alloys was also considered to serve as a main origin of weld porosity (hydrogen rejection) during laser welding (Refs. 2, 12, 13).

Measurement of the compositions of the entrapped gases in the preexisting micropores in the base metal, using quadrupole mass analyzer (Refs. 10, 11), showed that the main composition is nitrogen gas, ~95% by volume, with very little hydrogen gas, only ~1% (Ref. 10), which supports the entrapment of air in the base metal during die casting. After welding, the main composition of entrapped gases in the weld was also nitrogen gas, ~78%, but with significant increase in hydrogen gas.

KEYWORDS

Pore Formation
Laser Welding
Die-Cast Magnesium Alloys
Prevention Technique
Hydrogen

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necessary. The reduction of porosity is strongly correlated to increasing heat input, i.e., lower laser power and welding speed (Refs. 5, 6, 10, 11), or with decreasing interaction time (Ref. 2). Suppression of pore formation in these welding conditions should be attributed to the insufficient nucleation and growth time, as well as the rapid cooling rate of the weld pool (Refs. 1, 2). If hydrogen remains dissolved in solid magnesium and preexisting pores are not well swelled and coalesced yet, then the weld porosity can be reduced. However, reducing weld porosity by using low heat input is achieved with the sacrifice of penetration depth. Marya and Edwards’ work (Ref. 2) showed that pore-free welds could be readily obtained for normal-pressure die-cast magnesium Alloy AZ91 in all welding conditions employed (also see Ref. 20). For high-pressure die-cast AZ91, the lowest weld porosity, ~10%, was obtained using high welding speed, but with only a 0.65-mm-deep weld for a 3.5-mm-thick sheet. Similarly, using low heat input, Zhao and DebRoy (Refs. 5, 6) and Wahba et al. (Ref. 10) also obtained relatively low weld porosity in die-cast AM60B and AZ91D magnesium alloys, respectively, also without complete joint penetration. As a remedy, Zhao and DebRoy (Ref. 6) proposed to use a moderate laser power and perform a well-controlled remelting of the die-cast AM60B laser welds, which allows the entrapped gas bubbles in the welds to have a second chance to escape. At a high welding speed of ~6 m/min, this remedy led to a low weld porosity of ~6% but the penetration status was not mentioned in the report. Moreover, the weld porosity is sensitive to the remelting parameters and the choice of appropriate remelting parameters is of vital importance. Wahba et al. (Ref. 10) proposed to perform welding of a butt joint with an extracted magnesium alloy insert layer to reduce the weld porosity in die-cast AZ91D, instead of using low heat input. Weld porosity as low as ~5% was obtained but the method itself is of less practicality in actual industrial applications due to its complexity.

There were also reports showing that lower laser power and welding speed could reduce weld porosity in die-cast AZ91 magnesium alloys (Refs. 2, 21, 22), since long interaction time favors the degasification. However, weld porosity of 18% was obtained even when the welding speed was only 0.15 m/min (Ref. 2). So far, it is still challenging to effectively and expediently produce pore-free and complete-joint-penetration laser welds in high-pressure die-cast magnesium alloys.

In the present study, gas compositions both entrapped in micropores and dissolved in the base metal of 2.54-mm-thick high-pressure die-cast magnesium Alloy AM50 sheets are measured to better understand the origin of high weld porosity during laser welding.
welding. Then the effects of welding parameters on weld porosity are systematically investigated using both CO₂ and fiber lasers, and a prevention technique of pore formation is realized. Welds with low porosity (<5%), complete joint penetration, and good surface quality are obtained. The control strategy of this technique is also presented. For thicker sheets, 5 mm in thickness, the gas content in the base metal is lower due to its greater mass (assuming the same amount of entrapped gas) and lower casting pressure, and weld porosity can be reduced more readily, thus the results are not presented.

**Experimental Procedures**

**Analysis of Gas Compositions in the Base Metal**

The material investigated in this study was 2.54-mm-thick high-pressure die-cast magnesium Alloy AM50. Chemical compositions of the base metal are shown in Table 1. Two types of gas composition analyses were performed for the base metal. The first is inert gas fusion analysis (IGFA). The AM50 sheet was cut into a 60 × 20 × 2 mm block, mechanically cleaned with a metal scraper, and then fused by heating it to a temperature of 700°C (the liquidus temperature being 640°C) for 0.5 h in a quartz tube in argon gas current. The compositions of released gases, including solute hydrogen released as molecular hydrogen (H₂), were collected and measured using gas chromatography. Since gas chromatography only gives the volume ratio of each gas component, a certain amount of gas not contained in the base metal, 0.5 mL CO, was mixed into the collected gas and the absolute volume of each component can be calibrated according to the absolute volume of CO gas. The second analysis is similar to the IGFA, with the only difference being the lower heating temperature of 350°C and longer holding time of ~ 1 h. In the latter analysis, only gas dissolved in the base metal (atomic form, diffusible) can get released by diffusion, since the heating temperature is lower than the solidus temperature, ~ 434°C.

**Vacuum-Degassing of the Base Metal**

To ascertain the effect of solute hydrogen (atomic form) on weld porosity during laser welding, AM50 base metal was also vacuum-degassed to remove solute hydrogen (atomic hydrogen) through diffusion. The samples were mechanically cleaned and then vacuum-degassed (10⁻⁵ Pa) using an FF-160/620NE turbomolecular pump during heating. The temperature reached 350°C in about 0.5 h and then was kept for 1.5 h.

**Laser Welding Procedures and Parameters**

Bead-on-plate welds were produced on base metal sheets using a 3-kW CO₂ laser and a 6-kW fiber laser, respectively. The die-cast sheets were 200 × 18 × 2.54 mm in dimension, and surfaces were ground with 600-grit SiC paper and cleaned with acetone before welding. The CO₂ laser has a focal length of 300 mm, with a spot size of 0.6 mm in diameter, and the fiber laser has a focal length of 250 mm, with a spot size of 0.25 mm in diameter. Welding was conducted with the focal position on the workpiece surface. Figure 1 schematically shows the experimental setup. During welding, the workpiece was placed horizontally on an aluminum anvil with a horizontal square notch (5 × 5 mm) along the welding direction, which was just underneath the workpiece to provide shielding gas (argon gas, at a flow rate of 500 L/h) to the bottom surface of the workpiece. Meanwhile, a cylindrical copper nozzle (8 mm ID) was directed in the welding direction, which was just underneath the workpiece to provide shielding gas (argon gas, at a flow rate of 1000 L/h) to the top surface. The laser powers utilized varied from 0.5 to 2 kW, and the welding speeds varied from 1 to 10 m/min. Bead-on-plate welds were also produced on a 2.54-mm-thick wrought magnesium alloy AZ31 sheet and on a vacuum-degassed AM50 sheet for comparison, using the same welding procedures as depicted previously. In some cases, to characterize gas release from the weld pool during laser welding, optical images of high-temperature plasma plume were captured in real time by a high-speed CCD camera with a solar filter at a framing rate of 1000 f/s.

**Metallographic Examinations and Porosity Measurement**

After welding, welded samples were sectioned across the weld interface and mounted, followed by grinding, polishing, and etching (alcohol with 5% glacial acetic acid) procedures. Micrographs of weld cross sections were obtained using a metallurgical microscope. The area-percent porosity in the fusion zone of the weld cross section was measured through com-
Fig. 6 — Cross-sectional micrographs of welds produced on the following: A — Undegassed; B — vacuum-degassed die-cast AM50 sheets.

WELDING RESEARCH

puter image analysis using MATLAB software and an average was taken over three different cross sections of each sample.

Tensile Testing of the Joints

Welds used for the tensile tests were produced on relatively large sheets, 200 × 200 × 2.54 mm. After welding, samples were sectioned into 20-mm-wide rectangular sheets across the weld interface. The tensile specimens were 200 × 20 × 2.54 mm in dimension (length and width of reduced section being 50 and 12 mm, respectively), with length perpendicular to the weld interface, as shown in Fig. 2 (top view). Before testing, both front and back surfaces were machined. The tensile tests were carried out at a travel speed of 2 mm/min (strain rate being 7 × 10⁻⁴/s) at room temperature until failure. The strength was taken as an average of three specimens from the same welded sample. Microstructural images of fracture surfaces were examined with scanning electron microscopy (SEM).

Results and Discussion

Gas Compositions in the Base Metal

Although it has been known for a long time that gases entrapped in the base metal of magnesium alloys during the die-casting process have significant effects on pore formation during laser welding (Refs. 2, 4–6, 10), examinations of the gas compositions were performed only for gases entrapped in the micropores (initial porosity 2–5%) of the base metal (Refs. 10, 11), and nitrogen gas was found to be the main composition. Measuring the compositions of dissolved gas (atomic form) in the base metal of die-cast magnesium alloys has not been reported yet, and therefore their effects (especially hydrogen effects) on pore formation during laser welding were not evaluated relevantly. Using inert gas fusion analysis (IGFA), the total gas compositions in the base metal of high-pressure die-cast magnesium Alloy AM50 were measured after fusion, and results are presented in Table 2. It is found that the base metal indeed has a high gas content, 63.4 mL/100 g, noting that the values for low-pressure castings and vacuum die castings are only 1–5 mL/100 g and < 3.5 mL/100 g, respectively (Ref. 23). The major composition (72.1% in volume) of the gas content is hydrogen, 45.7 mL/100 g (the average solubility of hydrogen in solid magnesium being 30 mL/100 g from Ref. 1). Differing from gas composition analysis using a quadrupole mass analyzer (Refs. 10, 11), nitrogen gas was not detected by IGFA, since nitrogen can react with magnesium at such a high temperature (700°C) and form nitride. Therefore, the IGFA results presented here should not be considered as inconsistent with those obtained by a quadrupole mass analyzer (Refs. 10, 11), but are complementary to each other.

The hydrogen content in the collected gas, 45.7 mL/100 g, should originate from two sources: hydrogen gas entrapped in micropores (molecular hydrogen H₂) and solute hydrogen dissolved in base metal (atomic hydrogen). To measure the fraction of hydrogen that originates from each source, the sample was heated to 350°C in argon gas current for ~1 h in a quartz tube. This temperature only allowed solute hydrogen (atomic form) to diffuse from the base metal and form hydrogen gas H₂, since it is very difficult for hydro-

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Table 3 — Porosity, Surface Quality, and Penetration of Welds under Different Welding Conditions

- Complete joint penetration; ○ Partial penetration; ▲ good surface quality; △ bad surface quality; ☆ Low porosity (<5%); ★ High porosity (>5%)
The abundant hydrogen in the base metal of die-cast AM50, 45.7 mL/100 g, should result from the interaction of water vapor (H₂O) with magnesium during the die-casting process. It is well known that the hydrogen solubility in magnesium is higher (average solid solubility ~30 mL/100 g from Ref. 1) than that in aluminum alloys (Ref. 6), and can be increased (Ref. 24) by the high casting pressure (22–70 MPa) (Ref. 25). During die casting, a large fraction of hydrogen should be dissolved in the liquid metal due to the higher liquid solubility (Ref. 6). During solidification, part of the dissolved hydrogen will be rejected from solid phase to liquid phase (Ref. 13) due to the decrease in hydrogen solubility at the liquidus (Refs. 6, 26). The rejected hydrogen will eventually form high-pressure hydrogen pores inside the base metal (Refs. 12, 13), since escape from the liquid at such a high casting pressure (22–70 MPa) is extremely difficult. The remaining solute hydrogen in solid magnesium could still be supersaturated, and is speculated to play an important role in pore formation during subsequent treatments, such as laser welding. The role of hydrogen in pore formation during laser welding could be similar to that during die casting, since the two solidification processes have some similarities. However, hydrogen rejection during laser welding could be more intense, considering the fact that the pressure on the weld pool is much lower than that during die casting, and the hydrogen solid solubility is reduced. This will be addressed in the following section.

### Weld Porosity Tendency and Effect of Solute Hydrogen

Bead-on-plate welds were produced on both a 2.54-mm wrought AZ31 and a 2.54-mm die-cast AM50 sheet using the same welding parameters (fiber laser, power 1 kW, welding speed 4 mm/min), to compare their different weld porosity tendencies. The weld bead surfaces of wrought AZ31 and die-cast AM50 sheets are shown in Fig. 3A and B, respectively. It is seen from Fig. 3 that the wrought AZ31 sheet has a flat, smooth weld surface, whereas the weld surface of die-cast AM50 sheet has obvious swells and open holes. Cross-sectional micrographs of these two welds are shown in Fig. 4. Apparently, die-cast magnesium alloy AM50 has higher weld porosity due to its high gas content (63.4 mL/100 g) in the base metal, in accordance with the results of Haferkamp et al. (Ref. 8). The difference in weld porosity is also reflected by their different gas release behavior during laser welding. As shown in Fig. 5 (side view), the ejection of plasma plume from the AM50 weld pool surface during laser welding is more intense and unstable than that from the AZ31 weld pool surface. Such an unstable and eruptible plasma plume ejection from the AM50 weld pool surface indicates the active behavior of bubbles (bubble formation, floating, and escape) inside the weld pool during laser welding, resulting in high weld porosity and bad surface quality. The flames observed, namely the color rim of the plasma spot as seen only in Fig. 5B, indicates that there are also inflammable gases released from the weld pool.

It was found in our previous work (Refs. 16, 19) that vacuum-degassing of the base metal of 2-mm-thick AM50 sheet before laser welding can reduce the weld porosity significantly. This indicates that solute hydrogen in the base metal plays a more important role than preexisting micropores in pore formation during laser welding. Similar to high-pressure pore formation by hydrogen rejection during solidification of the die-casting process as discussed in the previous section, melting and then solidification of the weld pool during laser welding will also lead to hydrogen rejection and form hydrogen pores in the weld. The pore formation process during laser welding may be even more violent due to the low pressure (~1 atmosphere) and rapid solidification. The low weld pool pressure reduces the solid solubility of hydrogen (Ref. 24) (more hydrogen has to be rejected) and also favors the growth of formed hydrogen pores to larger sizes (low internal pressure); while the rapid solidification of the weld pool suppresses escape of formed pores. As shown in Fig. 6A, cross-sectional micrograph of a weld produced on an undegassed 2.54-mm-thick AM50 sheet shows high weld porosity, whereas the vacuum-degassed weld produced at the same welding condition (CO₂ laser, 0.8 kW, 1.5 mm/min) has much lower porosity.
Effects of Welding Parameters on Weld Porosity and Discussion

Welding parameters, i.e., laser power and welding speed, were varied in a wide range in this study, to systematically investigate their effects on weld porosity, as well as penetration and weld surface quality. In total, there were seven different laser powers ranging from 0.5 to 2 kW, and 24 different welding speeds ranging from 1 to 10 m/min used for both CO2 and fiber lasers. Typical cross-sectional micrographs of welds produced by CO2 laser using different welding parameters are shown in Fig. 7. For both laser powers of 0.8 and 2 kW, weld porosity as well as penetration depth increase with decreasing welding speed, as shown in Fig. 7A–H. This is consistent with previous results by Zhao and DebRoy (Refs. 5, 6) and by Wahba et al. (Ref. 10). Low weld porosity can be obtained only when using low laser power and high welding speed (low heat input), accompanied with shallow penetration, as seen in Fig. 7A. Considering that weld porosity is dominated mainly by solute hydrogen in the base metal, therefore, a smaller weld pool, which contains less extra hydrogen diffused from the heat-affected zone during melting (hydrogen gathering, a reverse process of hydrogen rejection as during solidification), is speculated to have low weld porosity. To get a smaller weld pool without losing penetration depth, a fiber laser with smaller beam diameter (0.25 mm in diameter) was used instead of a CO2 laser (0.6 mm in diameter).

Typical cross-sectional micrographs of welds produced by fiber laser using different welding parameters are shown in Fig. 8. For low laser power of 0.5 kW, similar to CO2 laser welds, both weld porosity and penetration depth increase with decreasing welding speed, as shown in the first row of Fig. 8. Low weld porosity was obtained only when using high welding speed, accompanied with shallow penetration, as seen in Fig. 8A. For higher laser powers of 1 and 1.5 kW, weld porosity increases with decreasing welding speed first, reaching a maximum (rows 2 and 3, second column in Fig. 8), and then decreases, encouragingly, reaching a minimum (rows 2 and 3, third column in Fig. 8). A further increase in welding speed will increase weld porosity again (rows 2 and 3, fourth column in Fig. 8). Differing from welds with low porosity but also shallow penetration (Fig. 7A, first column of Fig. 8A), these welds with minimum porosity, as seen in rows 2 and 3, third column of Fig. 8, also have complete joint penetration, and therefore could be considered as sound welds. This was achieved only by selecting fiber laser power and appropriate welding speed, and could be easily applied in practical applications.

To obtain the laser-welding variables (combinations of welding parameters) that control pore-formation phenomenon in welds, variations in weld porosity with heat input at different laser powers are shown in Fig. 9. The independent variable being heat input (laser power over welding speed) was indicated by the fact that weld porosity increases monotonously with increasing heat input in some cases (Fig. 7, first row in Fig. 8, also see Refs. 5, 6, 10, 11). To allow quantitative comparison of weld porosity in both CO2 and fiber laser welds in spite of their different beam diameters, the beam diameter and laser power were grouped into a single variable, laser power density (laser power over spot area), accounting for both laser spot size and laser power. This single variable then was used to divide the variations of weld porosity into two categories, instead of using both laser type and power. For laser power densities less than 1.8 × 10^6 W/cm², weld porosity always increases monotonously with increasing heat input, as shown in Fig. 9A. This includes all CO2 laser welds and fiber laser welds produced at low power. Sound welds were neither obtained by using the CO2 laser nor by using the fiber laser at low laser power in this study. Moreover, the variations of weld porosity with heat input for both lasers have the same trend, as shown in Fig. 9A. It is indicated that, at low power density, the two lasers have common dependence of weld porosity (regularity) on welding variables.
welds. It is well known that weld porosity is governed by two processes: nucleation/growth of gas bubbles and their escape from the weld pool. If the former process overwhelms the latter, then the weld will have high porosity and vice versa. For wrought and sand-cast magnesium alloys that have low gas content, low weld porosity can be obtained at low welding speed, since the small amount of dissolved gas can only result in limited amount of gas bubbles (i.e., the bubble source is limited), yet the long interaction time favors the escape process (Ref. 27). For die-cast magnesium alloys that have high gas content, during laser welding the nucleation/growth process could be sustaining until all gas content exhausts, and whether it can be overwhelmed by the escape process is a key to obtain low-porosity welds. However, the competition between the two processes depends on many factors, such as heating and cooling rates, weld pool size, interaction time, etc., and could be very intricate. Taking welding speed as an example, at the same power density a lower welding speed will introduce more energy to the weld pool and generate a larger pool size, since energy loss through heat conduction from the pool to the base metal stays the same. Thus, it will take longer for the pool to cool down, favoring diffusion of solute hydrogen from the heat-affected zone to the weld pool (hydrogen gathering). As a result, more gas bubbles will be formed due to hydrogen rejection during solidification. On the other hand, longer cooling time also favors escape of formed gas bubbles, making the dependence of weld porosity on welding speed unpredictable. Actually, from Fig. 9B, it is clearly seen that the dominance of the latter process over the former depends not only on the welding speed but also on the laser power density used.

To better understand the dependence of the two processes on weld-pool thermal history (heating and cooling rates) and welding parameters, dynamic behavior of both atomic and molecular hydrogen during laser welding were systematically investigated (Ref. 28). A detailed presentation of the pore-formation mechanisms will be given in a separate report, since the present work mainly focuses on the prevention technique.

Control Strategy of the Prevention Technique

Besides low porosity and complete joint penetration, good surface quality is also a requirement for a sound weld. In general, a low-porosity weld corresponds to a flat, smooth surface, as shown in Figs. 8G and 10A, and vice versa (see Figs. 8H and 10B). However, at very high power density and low heat input, the weld pool is melted rapidly but also solidifies rapidly, resulting in low weld porosity but with bad surface quality, as shown in Fig. 10C (the porosity is ~5%). This should be attributed to the reduction of the molten pool fluidity due to rapid cooling, as well as eruption of gas bubbles. Qualities of all welds obtained in this study were assessed according to their weld porosity, penetration status, and surface quality; the results are summarized in Table 3. Only welds with low porosity (<5%), complete joint penetration, and good surface quality (flat and smooth) as marked by triple solid symbols in Table 3, are considered to be sound, and their corresponding cross-sectional micrographs are shown in Fig. 11. The operating window for the welding variables (laser power density and heat input) to obtain sound welds, as well as the major weld defects for defective welds is also presented, as shown in Fig. 12. It is seen that, for low heat input, welds have incomplete pene-
The weld porosity is always high due to the dominance of the gas bubble nucleation/growth process over escape process; for low heat input and low power density, welds have both incomplete penetration and high porosity; and for sufficient power density, a sound weld can be obtained only when using appropriate heat input. It is concluded that, in order to obtain sound laser welds with low porosity, complete joint penetration, and good surface quality, the laser power density should be greater than $1.8 \times 10^6 \, \text{W/cm}^2$ such that the variation of weld porosity with heat input minimizes at a moderate value where complete joint penetration is ensured, but less than $4.1 \times 10^6 \, \text{W/cm}^2$ to obtain good surface quality. For laser power densities of $1.8 \times 10^6$, $2.0 \times 10^6$, $3.1 \times 10^6$, and $3.7 \times 10^6 \, \text{W/cm}^2$, the corresponding optimal heat inputs should be within the range of $23~34$, $23~30$, $17~20$, and $17~18 \, \text{J/mm}$, respectively, to obtain sound welds with low porosity, complete joint penetration, and good surface quality. It is clear that the window size for the heat input is larger if a relatively low power density is adopted.

### Tensile Test of the Joints and Fracture Features

Uniaxial tensile tests were performed to determine the mechanical properties of the base metal and joints obtained using different welding parameters. Welding conditions and porosities of the tested joints are listed in Table 4, and the corresponding results are shown in Fig. 13. As seen in Fig. 13, both tensile strength and elongation increase with the decrease in porosity. Fractographs of the joints are shown in Fig. 14. As seen in Fig. 14, the fracture surface of the joint with high weld porosity has plenty of pores (see Fig. 14A), whereas fracture surface of the joint with low weld porosity has fewer pores (see Fig. 14B). The increase in tensile strength and elongation with decreasing porosity should be attributed to the increase in effective loading area, as shown in Fig. 13. When the porosity is extremely low (~0.4%), nearly pore free, as seen in Fig. 8K, the tensile strength is comparable to that of the base metal and the joint fractures in the base metal. Thus, it is concluded that the welds with low porosity obtained through the prevention technique have a joint performance comparable to the base metal.

### Conclusions

Analyses of gas compositions in the base metal of high-pressure die-cast magnesium Alloy AM50 were performed and solute hydrogen in the base metal was found to attribute to weld porosity during laser welding. Effects of welding parameters on weld porosity were systematically investigated, and an effective and expedient prevention technique was realized.

1. Analyses of gas composition in the base metal showed the base metal contains a high gas content, 63.4 mL/100 g, most of which is hydrogen (72.1% in volume). A fraction of the hydrogen, at least 38% in volume, is dissolved in the base metal in atomic form, and is found to contribute to the weld porosity during laser welding.

2. Effects of welding parameters (laser power and welding speed) on weld porosity were systematically investigated. It is found that, within the range of welding parameters investigated here, weld porosity and penetration depth increase with increasing heat input monotonously when laser power density is low for both CO$_2$ and fiber lasers; with sufficient fiber laser power density (> $1.8 \times 10^6 \, \text{W/cm}^2$), variation of weld porosity with heat input minimizes at a moderate value, which enables obtaining low porosity welds with complete joint penetration.

3. A prevention technique was realized to obtain sound laser welds with low porosity, complete joint penetration, and good surface quality: the laser power density should be greater than $1.8 \times 10^6 \, \text{W/cm}^2$ such that the weld porosity minimizes at a moderate heat input where complete joint penetration is ensured, but less than $4.1 \times 10^6 \, \text{W/cm}^2$ to obtain good surface quality. The operating window of laser welding...
variables were presented for the following laser power densities: 1.8 × 10^6, 2.0 × 10^6, 3.1 × 10^6, and 3.7 × 10^6 W/cm²; the corresponding optimal heat inputs should be within the range of 23–34, 23–30, 17–20, and 17–18 J/mm, respectively.

4. Tensile tests were performed to determine the mechanical properties of the joints. It is found that both tensile strength and elongation increase with decreasing weld porosity. This is attributed to the increase of effective loading area with decreasing porosity. When porosity is extremely low, the joint performance is comparable to the base metal.

Acknowledgments

The authors thank Dr. Shoumei Xiong at the University of Tsinghua for the donation of die-cast AM50 alloys, Dr. Rongshi Xiao at the Beijing University of Technology for valuable technical assistance in fiber laser welding, and Dr. Yizhe Tang at Johns Hopkins University for assistance in manuscript preparation. The authors gratefully acknowledge the sponsorship from National Natural Science Foundation of China (No. 50775124) and Research Fund for the Doctoral Program of Higher Education.

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