Mechanisms and Elimination of Spatter and Porosity in Gas-Metal Arc Welding of Magnesium Alloys

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Abstract—The original objective of this study was to make GMAW a versatile process for welding Mg alloys and reduce the Spatter, which can cause 50% or more loss of the filler metal and which has long hindered the use of GMAW for Mg alloys, and Gas porosity, which has hardly been studied in GMAW of Mg alloys. The widely used AZ31 Mg (~ Mg-3Al-1Zn) sheets were welded with its recommended AZ61 Mg (~ Mg-6Al-1Zn) welding wire. Spatter was very severe with conventional Mg GMAW as expected. The mechanism for spatter was established. In order to suppress spatter, the use of CSC-GMAW for welding Mg alloys was explored, which is an advanced GMAW process with controlled short circuiting (CSC). Spatter was eliminated and the reason explained. However, with either process severe gas porosity was encountered, much worse than that in Al GMAW. The porosity-formation mechanism was established. Porosity was eliminated either by cleaning the welding wire with sandpaper before welding or baking the welding wire before welding. Recommendations for preventing gas porosity in Mg GMAW based on the present study were made to both the manufacturers and users of Mg welding wires.

Key words: Automotive, Gas Metal Arc, Porosity, Magnesium Alloys, Short Circuiting, Spatter

I. INTRODUCTION

Gas Metal Arc Welding (GMAW) is a welding process which joins metals by heating the metals to their melting point with an electric arc. The arc is between a continuous, consumable electrode wire and the metal being welded. The arc is shielded from contaminants in the atmosphere by a shielding gas. GMAW had its beginning in the late 1940’s. It was developed to speed up welding that was being done by the Gas Tungsten Arc Welding (GTAW) process. GTAW is also an arc welding process shielded by shielding gas, but GTAW uses a non consumable tungsten electrode. The filler rod for GTAW is generally added manually at a much slower rate. GMAW was thus developed to make welding a faster, more profitable process. GMAW developed when GTAW was thought to be too slow a process to weld thick sections of aluminium. Whereas GTAW worked very well on thin gauges (literally melting the metals together without adding filler wire), GMAW became much more efficient and profitable for welding thicker materials. This became especially helpful during the years of World War II. During its early days, Gas Metal Arc Welding was generally done with small electrode wires, high heat, and shielding gases that were inert (nonreactive). Because an inert gas was used, the term Metal Inert Gas, or MIG welding, was used to refer to this process. This term is still a very common reference for the welding process, even though technically incorrect. The development over the years of the use of reactive shielding gases (Metal Active Gas – MAG welding) gave rise to the term Gas Metal Arc Welding, or GMAW. In addition to being more profitable on heavy aluminium elements, GMAW was refined to produce quality elements on other materials and thicknesses, both thin and thick. Thus, the GMAW process unfolded into becoming a major element in industry today.

1) GMAW can be done in three different ways:
   - Semi-automatic Welding - equipment controls only the electrode wire feeding. Movement of welding gun is controlled by hand. This may be called hand-held welding.
   - Machine Welding - uses a gun that is connected to a manipulator of some kind (not hand-held). An operator has to constantly set and adjust controls that move the manipulator.
   - Automatic Welding - uses equipment which welds without the constant adjusting of controls by a welder or operator. On some equipment, automatic sensing devices control the correct gun alignment in a weld joint.

2) Basic Equipment For A Typical GMAW Semi-automatic Setup:
   - Welding Power Source - provides welding power.
   - Wire Feeders (Constant Speed And Voltage-Sensing) - controls supply of wire to welding gun.
   - Constant Speed Feeder - Used only with a constant voltage (CV) power source. This type of feeder has a control cable that will connect to the power source. The control cable supplies power to the feeder and allows the capability of remote voltage control with certain power source/feeder combinations. The wire feed speed (WFS) is set on the feeder and will always be constant for a given preset value.
   - Voltage-Sensing Feeder - Can be used with either a constant voltage (CV) or constant current (CC) - direct current (DC) power source. This type of feeder is powered off of the arc voltage and does not have a control cord. When set to (CV), the feeder is similar to a constant speed feeder. When set to (CC), the wire feed speed depends on the voltage present, the feeder changes the wire feed speed as the voltage changes. A voltage sensing feeder does not have the capability of remote voltage control.

   1) Supply of Electrode Wire.
   2) Welding Gun - delivers electrode wire and shielding gas to the weld puddle.
   3) Shielding Gas Cylinder - provides a supply of shielding gas to the arc.

II. LITERATURE SURVEY

[1] In order to reduce fuel consumption and emissions, the automotive industry has been reducing vehicle weight by using lighter structural materials including magnesium alloys. [2] Magnesium (Mg) is the lightest metallic structural material and its specific strength (that is, the strength/density ratio) is excellent. Recently, the use of Mg alloys has been increasing rapidly worldwide, and the cost of Mg per kg has decreased below that of Al since 2004.[3]
The research interest in Mg welding has grown rapidly recently, with more than 100 publications in the past few years. Reviews on recent Mg welding research are available. Gas metal arc welding (GMAW) is not used much for Mg alloys. In general, GMAW is a very widely used process for welding common materials such as Al alloys, steels, and stainless steels. It has both good weld quality and high production rate, and it is easily automated. Unfortunately, Mg GMAW can suffer from severe spatter. Spatter is the expelling of filler metal (i.e., welding wire) droplets from the arc during welding. Severe spatter can make the weld messy and irregular in shape. The weld width and penetration depth can vary significantly along the weld, which may not be straight. Additionally, a significant amount of the welding wire can be wasted. Losses of 50% or more of the Mg filler metal from spatter have been reported. Lockwood pioneered the early work on GMAW of Mg alloys in 1963 and 1970. He welded AZ31 Mg with an AZ61 welding wire. He tried various levels of wire feed rate, and hence welding current, from spray transfer at high currents to globular transfer at intermediate currents and short circuiting transfer at low currents. The transfer of molten filler metal to the weld pool was stable except for globular transfer, which was unstable and caused spatter. Spray transfer could not be established without using very high welding currents, much higher than those for GMAW of Al. Thus, spray transfer worked only for thick sheets (> 4.8 mm or 3/16 in.), and short circuiting transfer was used for thinner sheets (1.0–3.2 mm or 0.04–0.125 in.). In order to improve the bead contours and penetration over those with short circuiting transfer, he welded AZ31 Mg sheets 1.6–6.4 mm (0.063 – 0.250 in.) by pulsed-spray transfer at intermediate currents. That is, filler metal transfer was no longer globular but became stable with one small droplet transferred per pulse. After that, investigation of Mg GMAW seemed to stop.

Recently, the study of GMAW of Mg alloys has resumed. In 2004, in Germany, Rethmeier et al. used short circuit GMAW (GMAW-S) to weld AZ31 Mg and AZ61 Mg 1.35–2.5 mm (0.053–0.098 in.) in thickness with an AZ61 welding wire. Spatter was eliminated. In the same year in Japan, Ueyama et al. maintained a stable droplet transfer by using pulsed GMAW (GMAW-P). In 2010, in China, Song et al. used AC GMAW-P to weld AZ31 Mg 3.0 mm (1.18 in.) in thickness with an extruded AZ31 Mg wire as the filler metal. It was reported in both studies that spatter was effectively reduced or eliminated. In 2012, in China, Zhang et al. reported significant spatter reduction in conventional GMAW of 6-mm-thick AZ61 Mg plates by pre coating the work piece surface with a KCl flux. The authors are unaware of any new published reports on GMAW of Mg alloys conducted in the United States since 1970. Unlike spatter, gas porosity in GMAW of Mg alloys has hardly been studied at all. Lockwood reported gas porosity caused by welding Mg without first degassing the work piece surface. Both laser beam welding (LBW) and electron beam welding (EBW) have been used to weld Mg alloys. Deinzer et al. pointed out that a major limitation of LBW and EBW is that the equipment is expensive and not readily available. Also, gas porosity has been observed in LBW and EBW of Mg alloys. In either case, the high welding speed and deep/narrow weld pool impede gas bubbles from escaping from the weld pool before solidification. The problem is exacerbated when welding as-cast Mg alloys due to pre existing gas pores. In LBW of die-cast AM60 Mg, pre existing pores coalesced into large pores in the fusion zone. In LBW of thixomolded Mg alloys, the air entrapped during the mould-filling process caused severe gas porosity. Gas tungsten arc welding (GTAW) can be used to weld Mg alloys successfully. However, GTAW in general has a low production rate and requires a high level of welding skill, thus is often more suitable for repairing than mass production. An Ar/H2 shielding gas was used in GTAW of AZ80 Mg without a filler metal, and gas porosity was observed. Friction stir welding (FSW) can be used to weld Mg alloys successfully. According to the Welding Institute (where FSW was invented), the work piece must be rigidly clamped, a backing bar is required, and joints that require metal deposition cannot be made. In the construction of vehicle space frames, there can be many T-joints requiring metal deposition, which are very easy for GMAW. Deinzer et al. pointed out that a limitation of FSW is that the best use is with long and straight welds.

In summary, a versatile welding process is needed for Mg alloys in order to accelerate their use as a light structural material. GMAW, which has been widely used for Al alloys, steels, and stainless steels, has the potential to be such a welding process, but its application to Mg alloys is still very limited. Severe spatter has been the most frequently mentioned problem hindering Mg GMAW. It is very likely that severe gas porosity in Mg GMAW, though not reported so far, has been encountered in practice, and thus further discourages the use of GMAW for Mg alloys. The present study deals with spatter and porosity in GMAW of Mg alloys. The mechanisms of the formation of spatter and porosity were established and their elimination demonstrated. Both a conventional GMAW and an advanced GMAW process were used and the resultant welds compared. The goal was to make GMAW a versatile process for welding Mg alloys in order to help accelerate the use of Mg alloys.

III. EXPERIMENTAL PROCEDURE

A. Materials:
AZ31B-H24 Mg alloy sheets were welded. This is the most widely used wrought Mg alloy, and its nominal composition is Mg-3Al-1Zn by wt-%. The sheet was 203 mm long, 76 mm wide, and 1.6 mm thick (8x3 x1/16 in.), and was bead on-plate welded along the centre line in the length and rolling direction. Before welding, the work piece was degreased with acetone, the oxide film was removed in the area intended for welding with a stainless steel brush, and cleaned with acetone again. It was found that in butt joint welding of Mg alloys, the faying surfaces and the root opening between them can affect the porosity in the resultant weld. Therefore, to keep them from affecting gas porosity. Two AZ61A Mg welding wires with 1.2 mm (3/63 in.) diameter, filler metals A and B, were purchased from two different Mg welding wire suppliers. The nominal composition of AZ61 Mg is Mg-6Al-1Zn by wt-%. AZ61A Mg is the recommended welding wire for welding AZ31 Mg alloy. Filler metal A, which was purchased first, needed to be cleaned by the supplier before shipping. Filler metal B,
on the other hand, was brand new and thus required no cleaning.

B. Conventional GMAW:

Conventional GMAW was conducted using the In vision 456 power source and the welding conditions were as follows: Unless otherwise stated, the wire feed rate was 122 mm/s (288 in./min), the travel speed 7.6 mm/s (18 in./min), the voltage 19 V, and the contact-tube-to-work piece distance 12.7 mm (0.5 in.). The shielding gas was pure Ar at the flow rate of 275 cm3/s (35 ft3/h). The work piece was held down by steel clamps to prevent movement during welding. Two steel rectangular bars were placed between the work piece and the clamps, one on each side of the area intended for welding. Consequently, deposition of Mg vapour (and perhaps some Zn vapour as well) occurred on the work piece surface only in the area between the bars.

C. CSC-GMAW:

A controlled short circuit (CSC) version of the GMAW process was used. There are other controlled short circuit GMAW processes, for instance, CMT (cold-metal transfer) and STT (surface tension transfer). In CSC-GMAW, the process controller coordinates the feeding and speed of the wire electrode with the level of welding current delivered by the power source. Briefly, the welding process has two primary phases: the arc phase during which heat is generated to melt the base metal, and the short circuiting phase during which the filler metal droplet is deposited when the welding wire makes contact with the weld pool. The controller monitors the voltage between the electrode and the work piece to determine which phase the process is in at any given time. The controller clears the short by retracting the wire to the preset arc length level. Once the arc is established again, the controller begins feeding the wire toward the weld pool, and the cycle repeats. The waveforms of the welding current in CSC-GMAW can be tailored in great detail in order to optimize the welding process and reduce spatter. Examples of the details that can be specified include: 1) current levels and durations (for the start and mid periods) of the arc phase and those of the short circuiting phase; 2) the wire down speed, the delay before wire down, the wire up speed, and the delay before wire up; 3) the arc length; and 4) the penetration delay. The travel speed was 7.6 mm/s, the contact tube-to-work piece distance was 12.7 mm, and the shielding was pure Ar at the flow rate of 275 cm3/s (35 ft3/h). The same In vision 456 power source used for conventional GMAW was used. All that was needed was to connect the power source to the process controller and a welding gun with a wire-drive assembly dedicated to CSC-GMAW.

D. Data Acquisition:

The waveforms of the welding current and arc voltage were recorded using a computer data-acquisition system together with Lab View software. The data-sampling rate for each signal was 15,000 Hz.

E. High-Speed Photography:

A high-speed camera was used to record the arc and filler metal transfer during both conventional GMAW and CSC GMAW.

F. Examination of Welds:

The top surfaces of the resultant welds and the work piece were examined visually before and after cleaning with acetone. The welds were then cut in the longitudinal direction along the weld centre line, polished and etched with a solution consisting of 5 mL of acetic acid, 2.1 g of picric acid, 5 mL of distilled water, and 35 mL of ethanol for 2 s. The welds were then examined under an optical microscope to check for porosity inside.

G. X-Ray Diffraction:

To identify any compounds on the welding wire surface that may have contributed to gas porosity in the welds, powder was removed from the welding wire surface with a sharp blade for x-ray diffraction (XRD). One significant advantage of this system is that the amount of powder available can be very small.

IV. SPATTER AND ITS ELIMINATION

[5] As expected, severe spatter was encountered in welding AZ31 Mg by conventional GMAW. Figure 1A shows the top view of a weld made by conventional GMAW in the as-welded condition. As shown, the weld and its surrounding area between the steel clamping bars were covered with deposited vapour and spatter. The wire feed rate was 93 mm/s (220 in./min), the travel speed 8.5 mm/s (20 in./min), and the voltage 19 V. Unlike conventional GMAW, welds made by CSCGMAW were essentially spattered free. Figure 1B shows the top view of a weld made by CSC-GMAW in the as-welded condition.

![Fig. 1](image)

Fig. 1: Top views of bead-on-plate welds in the as-welded condition. That is, before removing vapour deposit and spatter.

A: Conventional GMAW showing spatter;

B: CSC-GMAW showing no spatter.

V. MECHANISMS OF SPATTER FORMATION AND ELIMINATION

[5] The mechanism of spatter in conventional GMAW was established based on both the transfer of the filler metal and the waveforms of the current and voltage recorded during welding. In fact, unlike previous studies, the waveform of power was also shown to further explain the spatter mechanism. The high-speed videos of spatter indicate that severe spatter occurs mainly because of excessive globule growth before short circuiting, that is, to provide a very
large globule for the arc to expel and cause spatter. As explained previously, the excessive growth is caused by the very low Mg density. Figure 2 shows a series of photos taken from a video. As mentioned previously, the globule is pushed forward by the arc to nearly horizontal -Fig. 2A. Unlike the vertical position, the horizontal position provides unlimited space for the globule to grow longer. As can be expected, as the globule grows longer, it also grows fatter to approach the weld piece -Fig. 2B. Short circuiting occurs when the globule touches the weld pool or the work piece -Fig. 2C. The arc reinitiating (Fig. 2D) after short circuiting is followed immediately by a sudden arc expansion (Fig. 2E) to expel the globule -Fig. 2F. Sometimes spatter was significantly less than expected in spite of the very large globule formed during welding. A nearly horizontal globule could grow so far ahead of the weld pool as to land on the solid work piece instead of the weld pool. The globule, being farther away from the arc heat, and hence cooler, could solidify quickly upon contact with the solid work piece before arc expansion. Since the solidified globule was elongated and in line with the welding direction, it was subsequently re melted completely by the advancing weld pool. This made the weld bead non uniform, that is, higher and wider than average where this occurred, and lower and narrower than average just before it.

VI. POROSITY CAUSED BY WELDING WIRE A AND ITS ELIMINATION

Severe gas porosity was observed in welds made with as-received welding wire A, by both conventional GMAW and CSCGMAW. Figure 3 shows the porosity in a weld made by conventional GMAW with welding wire A. Some pores tend to have large openings at the weld surface-Fig. 3A. Small openings of pores are visible inside the large opening-Fig. 3B. Porosity exists throughout the weld metal, that is, in the fusion zone-Fig. 3C. During cutting of the weld for metallographic, roofs of some large holes broke off, leaving behind large open pits on the weld surface. As shown in Fig. 4, porosity also exists throughout the weld made by CSCGMAW with welding wire A. The weld is irregular in shape. In fact, some spatter can be seen, even though it is supposed to be eliminated by CSCGMAW. The coexistence of porosity and spatter seems to suggest that the conditions causing severe porosity may also make the arc erratic to cause spatter. It can be seen in Figs. 3C and 4B that the pores tend to grow upward and forward (in the welding direction), that is, essentially normal to the solidification front during welding. With both spatter and porosity being severe, it is not difficult to imagine why GMAW has not been used much for welding Mg alloys. The level of gas porosity in the welds is far beyond that encountered in normal GMAW of common Al alloys. Examination of welding wire A reveals dark areas on the wire surface as shown in Fig. 5, where the wire segment is rotated to show how the dark areas vary on the surface. The 90- and 270-deg angles correspond to the inward- and outward-facing surfaces of the wire segment respectively before it was cut and removed from the spool for photography. The partially dark surface of welding wire A indicates its supplier did not or could not clean it thoroughly before shipping. To determine whether the dark areas on the surface of welding wire A were responsible for causing severe gas porosity, the areas were removed by polishing the wire surface with sandpaper followed by acetone cleaning. The cleaned wire is shiny, as shown at the bottom of Fig. 5. Removing the dark areas from the surface of welding wire A eliminated porosity from Mg welds made by both conventional GMAW and CSC-GMAW. It is clear that the dark areas on the welding wire surface caused severe gas porosity in welds made by both conventional GMAW and CSC-GMAW.
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In view of the porosity caused by the partially dark surface of welding wire A, a brand-new spool of welding wire with a shiny surface was used and the welds were porosity free as shown by the CSC-GMA weld in Fig. 7. This wire, called welding wire B hereinafter, was a 1.2-mm AZ61A welding wire ordered from a different supplier. The as-received welding wire was clean, free of any dark surface. However, welds made after welding wire B had been exposed to air for a few months show considerable porosity, as can be seen in Fig. 8. Examination of welding wire B, as shown in Fig. 9, indicated that dark areas had formed on the wire surface. Again, the 90- and 270-deg angles correspond to the inward- and outward-facing surfaces of the wire segment, respectively, before it was cut and removed from the spool for photography. The outward-facing surface of the wire appears darker because it was exposed to air and hence subjected to atmospheric corrosion. Removal of the dark areas from the surface of welding wire B eliminated porosity from welds. The cleaned wire surface was shiny and free of dark areas as shown at the bottom of Fig. 9.
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VIII. MECHANISM OF POROSITY FORMATION

The mechanism for the formation of gas porosity in GMAW of Mg alloys is proposed in Fig. 10A. As shown, hydrogen can come from three different places: the welding wire surface, the work piece surface, and the work piece interior. Firstly, if the welding wire is covered with hydrogen containing compounds, the compounds can decompose upon heating by the arc and release hydrogen into the arc. This hydrogen can dissolve in both the welding wire droplets and the weld pool. Hydrogen dissolved in metal is denoted as H. Since the surface area per unit volume of Mg is much larger with the welding wire than with the work piece, the welding wire can easily be the primary source of hydrogen porosity if it is indeed covered with hydrogen- containing compounds. Secondly, if the work piece is covered with hydrogen containing compounds (such as grease, moisture, etc.), hydrogen can enter the weld pool. Lastly, if pores pre exist inside the work piece (such as air bubbles trapped in liquid Mg during meld filling in die casting), they can enter the weld pool as bubbles upon melting the work piece during welding.

IX. CONCLUSIONS

The present study on GMAW of Mg alloy sheets aims to both establish the fundamental mechanisms of spatter and porosity formation and offer practical solutions to eliminate them. This will help make GMAW a versatile process for welding Mg alloys, which is still not available in spite of the rapidly increasing use of Mg alloys for weight reduction. The conclusions are as follows:

1) Exploration of the use of CSCGMAW for welding of Mg sheets has shown that spatter, which is often severe with conventional GMAW, can be eliminated.

2) Based on both the high-speed videos (at 4000 fps) of molten-metal transfer from the welding wire tip to the weld pool and the detailed waveforms of current and voltage recorded during welding, the mechanism of spatter has been established and the elimination of spatter by CSCGMAW has been explained.

3) The mechanism of spatter formation in conventional GMAW of Mg alloys is as follows: The low density of Mg is good for vehicle weight reduction but, unfortunately, bad for GMAW. Because of the very low Mg density, the welding wire melts easily and the melt keeps hanging onto the wire tip to grow into an excessively large globule by the time it touches the weld pool to short circuit. This provides considerable amounts of molten filler metal to be expelled as severe spatter by the sudden arc expansion immediately following arc re initiation from the short circuit.

4) Because of the very low density of Mg (about one-third less than that of Al), the energy required for melting the Mg welding wire is very low (42% less than that for melting an Al welding wire of the same diameter) and the globule is light and thus difficult to detach by gravity. Consequently, the globule can be expected to form easily and keep on growing until it touches the weld pool to cause short circuiting.

5) To make matters worse, the low Mg density allows the light globule to be pushed away easily from the weld pool and thus continue to grow until it becomes...
excessively large. Without being pushed away, the globule can only grow vertically down to the size limited by the distance between the wire tip and the pool surface.

6) Conclusions 4 and 5 explain the very high current needed to pinch off the molten filler metal by the Lorentz force and establish spray transfer in conventional GMAW of Mg, which unfortunately provides too much heat for welding Mg sheets.

7) The current and voltage waveforms show a large current surge during short circuiting, typical of conventional GMAW designed to spontaneously increase the current sharply to instantaneously melt back the welding wire, which quickly brings the arc length back to normal automatically and thus makes manual GMAW easy (much easier than manual GTAW). Unlike in previous studies, however, the waveform of power (= current x voltage) is also presented, and it reveals a power surge immediately after arc re-initiation, when the voltage has already recovered but the current, though falling, is still very high.

8) The power surge heats up the arc plasma instantaneously and causes a sudden arc expansion to expel the globule. The short-circuiting time (~2 ms) is too short for the large light globule to enter the weld pool before arc expansion.

9) Unlike the constant voltage mode, the CSC mode of GMAW is set up to control the current instead of voltage. The globule is smaller, and the much longer short-circuiting time (~18 ms) allows the globule to enter the pool. More importantly, the large current surge upon short circuiting can be limited, thus eliminating the power surge and hence spattering. In CSC-GMAW, the waveform of the welding current can be tailored in great detail to optimize the welding process.

10) Unlike in Al GMAW, severe gas porosity can occur in Mg GMAW, either conventional GMAW or CSC-GMAW, if the welding wire has been exposed to open air for an extended period of time.

11) Based on X-ray diffraction of the surface layer removed from the welding wire and the solubility of hydrogen in Mg as a function of temperature, the mechanism of porosity formation has been established.

12) The mechanism of porosity formation in GMAW of Mg alloys is as follows:

- With its large surface area per unit volume, a welding wire covered with Mg(OH)2 can carry a significant amount of Mg(OH)2 into the arc, where it decomposes by

\[ \text{Mg(OH)}_2 \rightarrow \text{MgO} + \text{H}_2\text{O}. \]

- The H2O further decomposes to hydrogen to dissolve in Mg(L) as atomic hydrogen. Since Mg(S) can dissolve much less H than Mg(L), it rejects H to form a H-rich liquid layer at the solidification front, where the high H concentration can push the reaction 2H → H2(g) to the right and form hydrogen porosity.

13) Mg(OH)2 has been identified on the surfaces of the welding wires that caused severe gas porosity, by using a special X-ray diffraction system that works even with a very small amount of powder removed from the wire surface. The surface appears dark where Mg(OH)2 exists. Mg welding wires can react with moisture in the air to form Mg(OH)2, that is, atmospheric corrosion.

14) The much more severe gas porosity in Mg GMAW than in Al GMAW is caused by:

- Much more hydrogen is available to dissolve in the Mg weld pool because Mg(OH)2 forms much more easily on a Mg welding wire than Al(OH)3 does on an Al welding wire.

- Much more hydrogen can actually dissolve in the Mg weld pool because of the much higher hydrogen solubility in Mg(L) than Al(L) (by about 60 times at the melting point),

- Much greater hydrogen-solubility drop occurs upon solidification of Mg (L) than Al (L) (by about 20 times), causing much more H rejection into the liquid at the solidification front to trigger the reaction 2H → H2(g), and

- H2(g) bubbles rise to escape from a Mg weld pool more slowly than an Al weld pool because of the lower density of Mg.

15) Cleaning the Mg welding wire with sandpaper before welding can eliminate gas porosity by eliminating Mg(OH)2. Baking the Mg welding wire in air at 380°C for 11 min before welding can eliminate gas porosity by making the reaction Mg(OH)2 → MgO + H2O occur before, instead of during, welding.

16) Recommendations for porosity prevention in GMAW of Mg alloys have been made, based on the results of the present study, to both the manufacturers and users of Mg welding wires.

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