Athens Institute for Education and Research
ATINER

ATINER's Conference Paper Series
IND2017-2334

New Experiences in Welding Magnesium Alloys

Peter Boehm
Professor
University of Applied Sciences Trier
Germany

Jannis Marion
Student
University of Applied Sciences Trier
Germany

An Introduction to ATINER's Conference Paper Series

ATINER started to publish this conference papers series in 2012. It includes only the papers submitted for publication after they were presented at one of the conferences organized by our Institute every year. This paper has been peer reviewed by at least two academic members of ATINER.

Dr. Gregory T. Papanikos
President
Athens Institute for Education and Research

This paper should be cited as follows:

Boehm, P. and Marion, J. (2017). **"New Experiences in Welding Magnesium Alloys",** Athens: ATINER'S Conference Paper Series, No: **IND2017-2334.**

Athens Institute for Education and Research
8 Valaoritou Street, Kolonaki, 10671 Athens, Greece
Tel: + 30 210 3634210 Fax: + 30 210 3634209 Email: info@atiner.gr URL: www.atiner.gr
URL Conference Papers Series: www.atiner.gr/papers.htm
Printed in Athens, Greece by the Athens Institute for Education and Research.
ISSN: 2241-2891
28/11/2017

New Experiences in Welding Magnesium Alloys

Peter Boehm
Jannis Marion

Abstract

The role of lightweight constructions is becoming more important in the automobile industry. In view of that fact, some structural elements in these industrial sections will be constructed of lightweight metal - magnesium. Magnesium alloys feature relatively suitable mechanical properties in relationship to their weight. Moreover, the process of casting magnesium is well known, so a great number of parts can be produced. Magnesium components are joined through screwing processes. Bolting connections have the disadvantage of being cost-intensive and sometimes run the risk of corrosion. To be more flexible in the construction of magnesium components, optimized joining technologies are demanded. Currently, only a comparatively low knowledge is available to join these magnesium alloys through welding technologies. To start solving the problem two different magnesium alloys, AZ91 and AM60 (two pressure casting alloys, different in aluminum content) were examined with different welding procedures, e.g. the TIG, the laser welding and the electron beam technology. In the course of the investigations, some material combinations like Mg/Mg or Mg/Al hybrid specimens were tested in verifying all main welding parameters. On the one hand, all welded specimen were tested against their mechanical-technological properties, particularly with regard to sufficient strength of the weld seams. On the other hand, the influences of the appearance of different solid solutions and different precipitation phases with a view to the structure of the weld were researched by metallographic methods, as well as by scanning electron microscope analyzing procedures. The results obtained by the investigations lead to precise indications of an optimized welding process for the examined material combinations. On the basic principle of fundamental knowledge of the precipitation creation, improved welding results for further material combinations can be expected.

Introduction

Magnesium is one of the most widespread materials on earth and also one of the lightest metals. The importance of magnesium in manufacturing increases day by day because of the need for lightweight constructions. New environmental regulations force the automotive industry and other sectors to look for new strategies. Light metals such as aluminium are self-evident in cars today. Composite materials, such as carbon or glass fibres, can also reduce weight, but they are expensive and difficult to machine after their first forming. Accordingly, production time and costs of industrial applications must be as cheap and reproducible as possible. New magnesium alloys can be used for many applications and can be formed in mass production by using casting. The enhancement of existing aluminium trusses, for example the Audi Space Frame, through the incorporation of magnesium alloys promises a reduction of weight by 20 percent.

Due to its high material costs and its moderate corrosion properties, magnesium was only used for unseen structures, such as gearbox covers, lower seat structures or dashboard structures in the past. In fact, the only application that most people associate with the use of magnesium as a construction material is a pencil sharpener. Others might think of their chemistry lesson when the teacher explains the earth alkali metals and their high reactivity with a burning magnesium wire. This might be the reason that some operators are afraid to use magnesium without cooling or welding it, although a solid piece of magnesium is hard to flame - even with a Bunsen burner.

Magnesium wrought alloys formed a negative image of magnesium in industry because of high costs. Moreover, they only have moderate formability due to the hexagonal lattice. Newly developed wrought alloys and production technologies improve the attractiveness of new application options, such as shell structures. In addition, the cost factor has been decreased with the effect that the price difference between aluminium and magnesium is negligible.

Complex constructions are only possible by joining components or assemblies. Therefore, the demand for better joining techniques has increased. The increase of aluminium constructions in the last few years was possible due to successful field-tested joining techniques. Nowadays, magnesium components are joined by screws, bolts or glue. This limits the scope of application and should be changed by applying other joining technologies. Welding magnesium with new welding processes can produce new possibilities. Hybrid welding with magnesium will also play a decisive role in the future. It can be expected that the economic use of such hybrid joins will estimate material technology within the next few years.[1, 2, 3, 4, 5]

Difficulties in Welding Magnesium Alloys

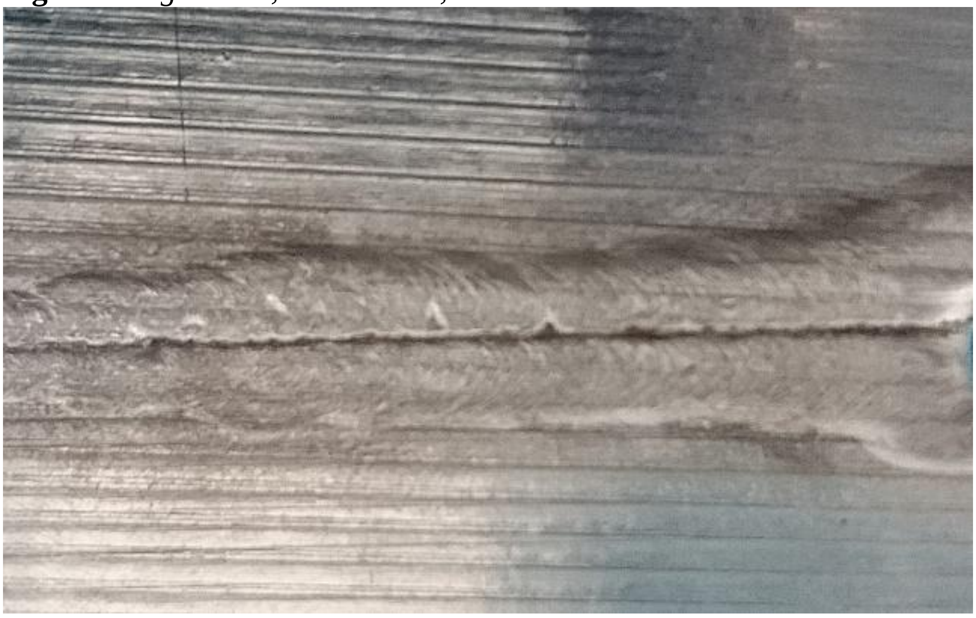
The welding of magnesium is difficult because there are many similarities to aluminium – one is the presence of the oxide-layer. Magnesium, just like aluminium, forms an oxide-layer on its surface; though it is much thinner, it causes the same problems. An alternating current (AC) is needed for tungsten inert gas welding, as the change in polarity cracks the oxide-layer. However, the oxide-layer should not be removed mechanically because it stabilises the welding-arc. The high rate of energy that is needed to crack the layer causes news problems as soon as it melts. The energy rate must be reduced for the base material under the surface because it has a lower melting point than the oxide-layer and is otherwise too liquid (Figure 1). The flow properties induce further problems as the liquidity of the melt gets too high. To solve the problem, a weld pool is necessary.

Figure 1. *Mg AM 60, TIG-welded, Leaked Melt on the Reverse Side*

Another question deals with the type of inert gas. Every inert gas or inert gas mixture has different properties. For example, helium and argon are both inert gases, yet they do not react with the weld in the same way. Helium expands the penetration.

Another problem connected to inert gas arises from the oxidation of magnesium. Similarly to stainless steel, magnesium reacts with atmospheric oxygen. Therefore, the inert gas needs to form a protective atmosphere. Stainless steel forms tarnishing on the back of the work piece, whereas magnesium oxidizes heavily (Figure 2).

Figure 2. *Mg AM 60, TIG-welded, Oxidation on the Backside*



Pulsation plays an important role in all welding processes. In the tungsten inert gas welding process using AC, the pulse current of the welding arc is essential although it is difficult to find the right frequency. If the frequency is too high, the liquidity of the melt becomes too high as well;

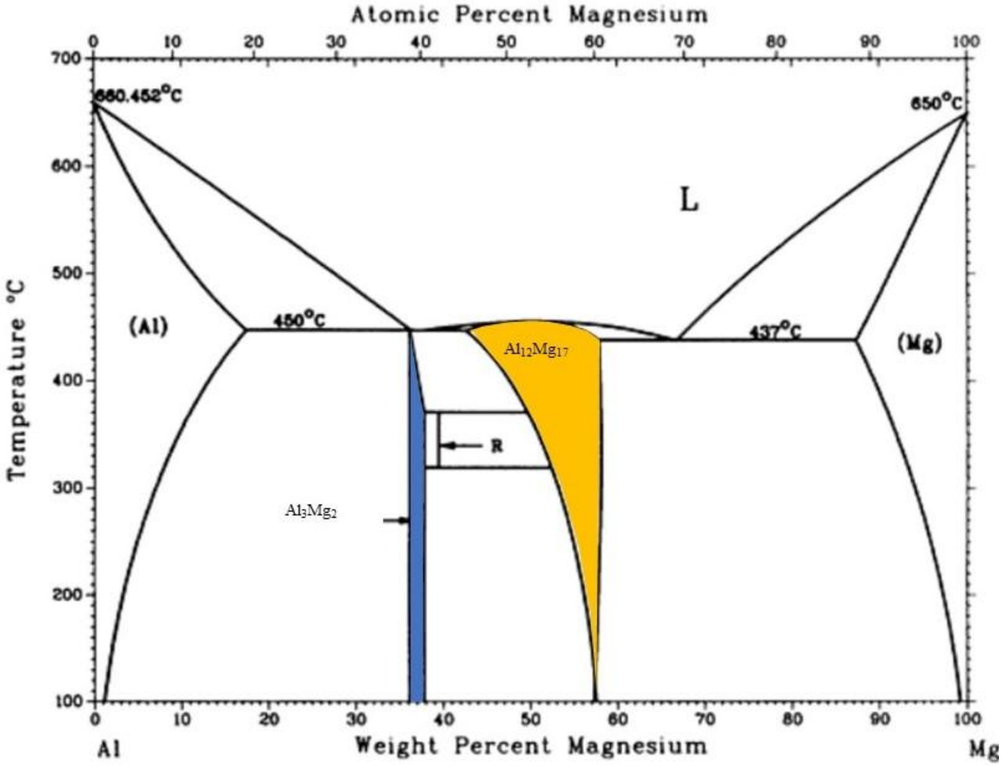
if it is too slow, the drops of the filler material get too big and will not really be melted. In laser or electron beam welding pulsation is essential to form the right keyhole.

As already mentioned, the energy rate, as well as the power, is one of the main problems. Primarily in laser and electron beam welding, the correlation between power and feed rate is essential. The power must be high enough to penetrate the material deeply enough, but without burning a hole. The variation of both components can still change the result without changing the energy density. In turn, the feed rate influences thermal expansion. Magnesium has a relatively high linear thermal expansion coefficient, even higher than aluminium. For this reason, welding materials should not be fixed while welding. Fixation during welding can create internal stress into the weld structure, which increases the risk of weld failures.

The formation of intermetallic phases is not always a problem, but some of them can weaken the welded joint. Phases with aluminium especially cause risk for the welding because some of them are extremely stiff and brittle in contrast to the main material being used. These undesirable intermetallic phases are coloured in

Figure **3**. The blue coloured so called β-phase (Al_3Mg_2) has to be avoided and plays a central role in hybrid welding between aluminium and magnesium.

Figure 3. *Phase Diagram Al/Mg, Intermetallic Phases*



The purpose of the study was to show that other welding techniques, besides tungsten inert gas welding, are possible. To compare commonly used welding techniques with the new ones, TIG welding was also tested.

Literature Review

Manufacturing Process

As already mentioned, magnesium and its alloys combine low weight with economical manufacturing. Characteristic advantages such as high casting rates, net shapes and long die life can be taken by using magnesium in pressure die casting.

In die casting molten metal is injected into a steel die before it is rapidly cooled. The aim of high-pressure die casting is to minimize the needed time per part. Furthermore, it has the unique ability to transform the injected molten metal into an accurately dimensioned and smoothly finished form.

Capabilities for Welding Magnesium

Lightweight constructions are becoming more and more important in order to reduce weight. It is also important to modernize joining techniques. In state of the art magnesium casts, components are fixed with screws or bolts, but this is costly and needs a lot of manufacturing time. The integration of die cast assemblies, for example in the automotive industry, demands new joining techniques for the maximum use of materials. Furthermore, joining with screws and bolts causes new problems as they are normally made of other materials such as steel, aluminium or titanium. One of the problems is a different thermal expansion of the materials. The linear expansion coefficient of magnesium is 24.8 µm/(m·K) (at 25 °C), while iron expands 11.8 µm/(m·K) (at 25 °C). In this case, the component is made of magnesium and the screw is made of iron; thus, thermal expansion generates additive stress.

Another problem lies in possible contact corrosion between magnesium components and, for example, steel screws, because magnesium is one of the most ignoble metals on earth with an electronegativity of 1.31 in the Pauling-scale in contrast to iron with 1.83. This problem can be avoided by using galvanic covers - if a covered specimen performs a fracture, the corrosion starts even worse than normally. Chrome covered bumpers used in cars produced in the 50s are an example of this problem. The bumper itself was made out of steel and covered with chrome. Whenever a stone or a similar object cracked this cover a galvanic corrosion between both components started. The welding of magnesium components cannot solve the problem, but might allow a change in the joint’s position with screws to a less critical one.

The welding of magnesium was discovered in 1924, but was not precisely described until 1929. Between 1960 and 1970 procedures such as tungsten or metal inert gas welding were investigated. Accordingly, the welding of magnesium is not a novelty, but the welding techniques have also improved in the last 50 years. New developments in electrical engineering and information technology have taken place. Newly discovered welding equipment and techniques, such as laser or electron beam welding, completely changed the possibilities. One of the most interesting capabilities is the hybrid welding of magnesium and aluminium. For example, if magnesium components are used for structural parts they have to be fixed with the main component. To realize a higher fastening torque without destroying the magnesium nut it can be advantageous to insert a nut made of aluminium. In this case, it can be realized by weld joining of both materials. Hybrid components or assemblies made of magnesium and aluminium could be used in the automotive and flight industries, or even for space applications.

Used Welding Techniques

Tungsten Inertgas Welding (TIG)

TIG is an acronym for **T**ungsten **I**nert **G**as welding and was firstly discovered in 1936 in the United States as so called “Argonarc” welding. In the beginning, the process was just used for special functions or high-class materials. Nowadays, TIG welding is one of the most common welding techniques and can be used for nearly every metal. The reason for its widespread distribution is its excellent welded join with a low transfer of heat in the base material.

The characteristic part of TIG welding is the non-consumable tungsten electrode. The electrode and the weld area are protected from oxidation with an argon (and/or helium) gas atmosphere. Argon is an inert gas and will not react with the weld. A constant-current welding power supply produces electrical energy, which is conducted across the arc through a column of highly ionized gas and metal vapors known as plasma. This plasma does not react with the welding area, but it transfers the electrical power across the arc into the base metal and starts the melting process. A filler material is mostly used to fill the gap. The difficulty is to feed the filler into the argon arc without touching the tungsten electrode or the weld area. Therefore, an experienced welder or a welding robot is essential. Moreover, all welding parameters have to be defined as well as possible. Welding parameters that can be changed are the length of the welding arc, the kind of current and its frequency, the kind of inert gas, the electrode diameter and form, as well as the amperage and voltage.

The welding properties of magnesium are similar to aluminium. To destroy the oxide-layer without overheating the tungsten electrode AC welding is preferred. However, the oxide-layer should not be removed mechanically because it stabilises the welding-arc. The main difference between this and aluminium is the lower level of energy that is needed to melt the joining zone (40 percent less energy than aluminium).[6, 7, 8]

Laser Welding

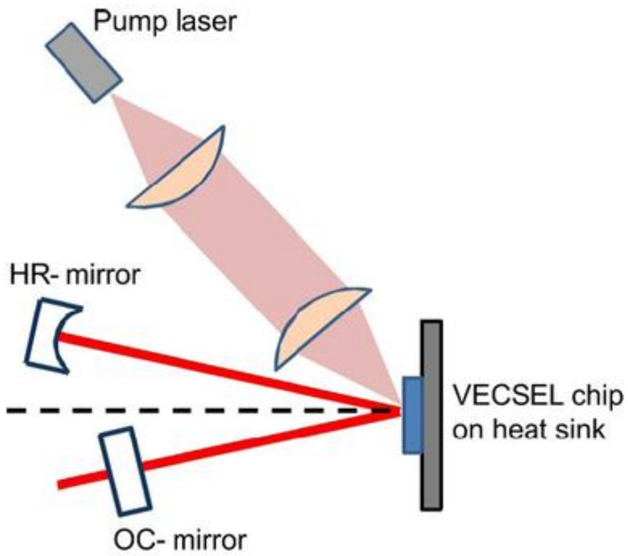
Laser is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. A laser uses focused light to transfer heat, in the same way that a loupe focuses sunlight. The difference between laser and sunlight is the used spectrum; sunlight exists in a wide spectrum, while laser light contains a typically smaller band of wavelengths. Different types of lasers produce different wavelengths. The first differentiation is the medium that generates light transmission. Nowadays, different laser types like gas, dye, metal-vapor, solid-state and semiconductor lasers will be used. For our research a solid-state disk laser was applied. A disk laser, or active mirror laser, is a diode pumped solid-state laser. They are called pumped lasers because the gain medium that forms the disk and generates the laser light has to be stimulated by a pump laser (Figure 4). Concerning the reflection coefficient of the gain medium, the disk laser uses some optical mirrors to raise its efficiency and to control the laser beam.

After stimulation by the pump laser, the gain medium generates its own light waves. The wavelength depends on the gain material and is a typical property of the used laser. To weld with laser light it has to be focused by refractors.

The weld parameters that can be regulated are the feed rate, the power and the focal point of the laser beam.

The advantages of laser welding in accordance to TIG welding are smaller heat deformations, a higher feed rate, and faster production. Besides that, no experienced welders will be needed anymore.[8, 9]

Figure 4. *Functional Principle of a Disk Laser[10]*



Electron Beam Welding

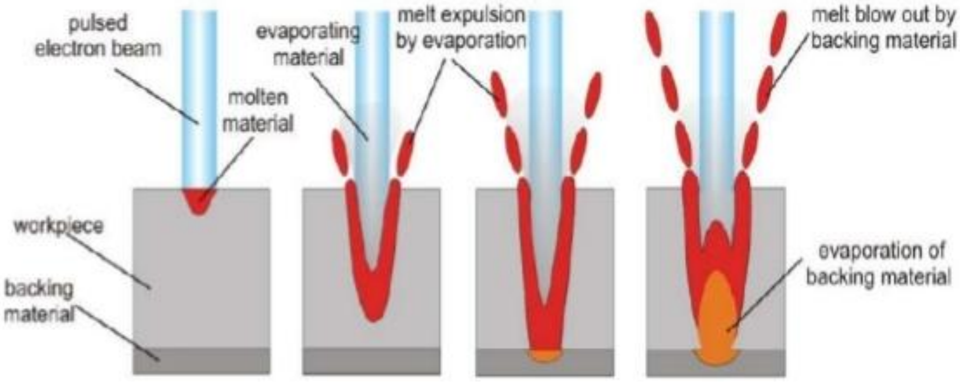
Electron beam welding (EBW) is a welding process that uses the kinetic power of electrons to transfer heat into the weld material. It was used for welding processes for the first time in 1958, and is used nowadays only for special applications. This is because EBW creates a high vacuum.

As mentioned before, the joining of the work piece must be applied under vacuum. Otherwise, the electron beam reacts with the particles of the air and ionises them. The beam is created in the cathode and is formed out of conduction electrons, which normally could not leave the metal unless their kinetic energy level is higher than the potential barrier at the metal’s surface. To realize this fact the cathode material is applied under high voltage of more than 30 kV. Following Richard’s Rule, the number of conduction electrons increases with increasing temperature. The used materials for those cathodes are tantalum or tungsten. The emitted electrons from the cathode leave with low velocity, as the kinetic energy also is small. To raise the kinetic energy level, the electrons are accelerated by a strong electric field. That field is generated by a positively charged electrode called an anode. With another negative electrode, the formed electron beam is controlled, and another electric field focus the focal point of the electron beam.

If the beam hits the surface some of the electrons penetrate the material while other ones reflect (so-called backscattered electrons). If the penetrating electrons hit an atom they transfer their kinetic power to the atom and produce heat. This effect happens basically in a thin layer under the surface. After creating the first melted zone on the surface the liquid metal gets more and more energy by the electron beam until a part of the melt vaporizes. The vaporized metal forms a so-called keyhole. By modifying the focal point and by placing it deeper into the keyhole, the output will be an expansion of the weld seam, as seen in Figure 5.

The weld parameters of electron beam welding are the voltage, the amperage, the feed rate, the focus, the electrode distance, and whether the electron beam is pulsed by frequency.[8, 9]

Figure 5. *Functional Principle of the Joining Process by EBW*



Used Materials

<u>Magnesium</u>

Metal magnesium was first isolated in 1808 by Sir Humphrey Davy. However, it took more than 100 years for its first application as a construction material. The real breakthrough of magnesium was during World War II as one of the main aerospace construction metals due to its low density. In 1944, annual production reached 228 kt. After the war, production decreased until the late 80s. At this time, there was a rediscovery of magnesium as a construction material. Turning into using magnesium was the advantage of weight reduction, and the lightweight principle applies in nearly every sector today. Carbon composites possess nearly the same density, but they are much more expensive and difficult to work with. Even aluminium is 30% heavier than magnesium. There are a few rare metals with almost the same mechanical properties, such as Beryllium, but they are too expensive for mass production or even toxic. A disadvantage of magnesium is its low corrosion resistance. According to its place in the periodic table, it is one of the most ignoble metals. However, there was a lot of research and development for new magnesium alloys. Although these new ones improve this to some extent, they cannot fully solve the problem.

Magnesium is an alkaline earth metal. It is found in Group 3 of the periodic table, together with Beryllium, Calcium, Strontium, Barium and Radium. Its properties are described in Table 1.

For this reason, the lattice parameters of pure magnesium at room temperature are close to the ideal value of 1.633 (magnesium 1.6236). Therefore, magnesium can be considered as perfectly closed packed.

The coefficient of linear thermal expansion depends on the temperature range. It can be expressed as a function regulated by the temperature (ΔT in Celsius).

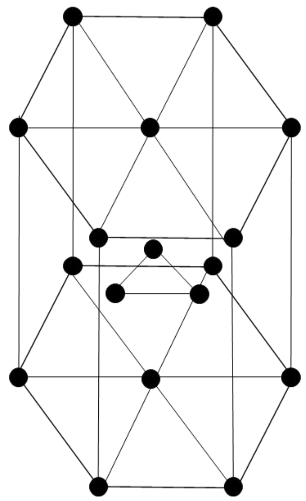
$$\alpha_T = (25.0 + 0.0188\,\Delta T) * 10^{-6}\,C^{-1}$$

Table 1. *Magnesium - Physical Properties*

Elementsymbol	**Mg**
Atomic number	12
Boiling point	1110 °C
Melting point	650 °C
Density	1.7
Elektronegativity	1.31 (Pauling-Scale)

The crystal structure is hexagonal close packed, Figure 6.[6]

Figure 6. *Magnesium Unit Cell*



Magnesium Alloy AM60

Magnesium requires additional alloying materials for use in engineering applications. The AM 60 alloy is optimized for pressure die casting and offers good ductility and energy absorption combined with good strength and castability. Moreover, it includes excellent machinability, good damping capacity, electromagnetic interference (EMI) and radio frequency interference (RFI) shielding properties. It consists of 6 percent aluminium, 0.3 percent manganese, and some parts of other components, as shown in Table 2. The typical use of AM 60 is for large thin-walled automotive parts with higher elongation and deformation requirements.

Table 2. *Alloying Components*

Al	Mn	Zn	Cu	Si	Fe	Ni	Pb	Be	Mg
%	%	%	%	%	%	%	%	%	%
6.24	0.3	0.07	0.0011	0.02	0.0022	<0.0003	0.0028	0.001	93.4

A high ratio of aluminium is typical for die casting alloys because aluminium improves strength and ductility above 6 percent of mass. However, the creep resistance is limited due to the small thermal stability of the $Mg_{17}Al_{12}$ phase, or the so-called γ-phase. The place of the AM60 cast alloy within the magnesium-aluminium phase diagram is defined in

Figure 7 by the red line.

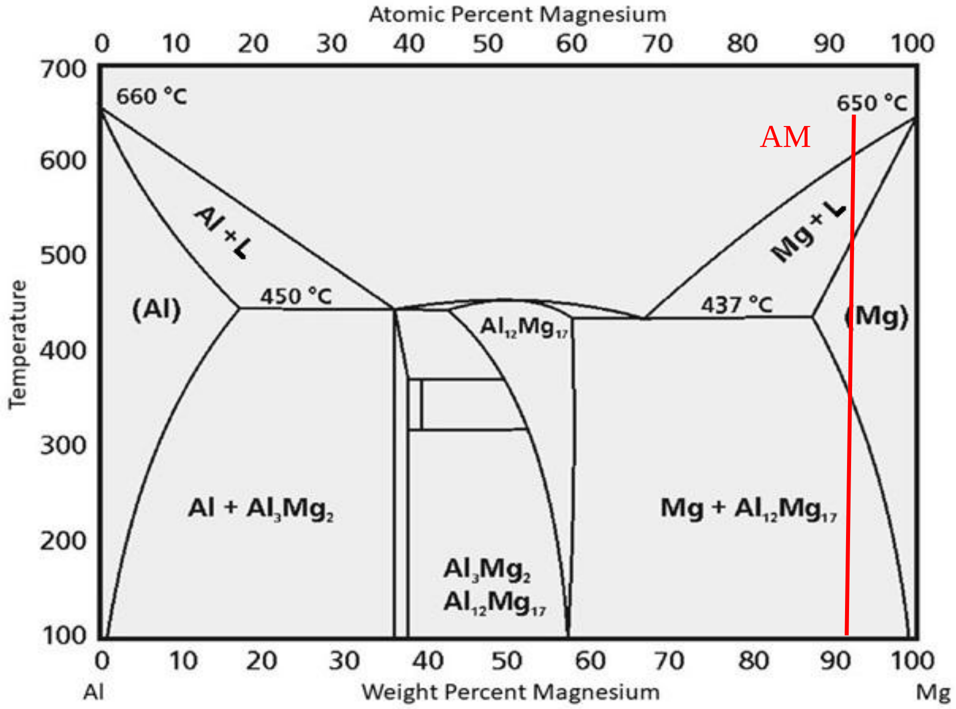
Manganese is often employed with aluminium because they form MnAl, $MnAl_4$ or $MnAl_6$ segregations, which reduce the solubility of iron. Besides that, manganese increases the yield strength and improves the saltwater corrosion resistance of MgAl alloys. The amounts of other elements are too low to influence the properties of the alloy so that new mechanical properties can be seen in

Table **3**.[7]

Table 3. *Mechanical Properties of AM 60*

Alloy	**AM60 cast alloy**
Tensile strength	230 MPa
Yield strength	130 MPa
Hardness	65 HB
Elongation	8-13 %
Elastic modulus	50 000 MPa

Figure 7. *Magnesium-Aluminium Phase Diagram*



Aluminium

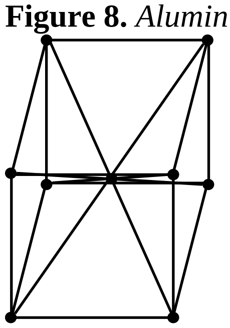
Aluminium plays a minor role in this study; however, the reason for a hybrid weld is to use the advantages of both materials. Therefore, some basic properties of aluminium are explained in

Table **4**. The lattice of aluminium, contrary to magnesium, is a face-centered cubic arrangement (Figure 8).

Table 4. *Basic Properties of Aluminium*

Elementsymbol	**Al**
Atomic number	13
Boiling point	2470 °C
Melting point	660 °C
Density	2.7
Elektronegativity	1.61 (Pauling-Scale)

Figure 8. *Aluminium Unit Cell*[6]



The aluminium alloy used is called AlMgSi1 and is a wrought alloy with 1 percent magnesium and nearly 1 percent silicon. It can be hardened by heat treatment and has good welding and mechanical properties (Table 5).[8]

Table 5. *Mechanical Properties of AlMgSi1*

Alloy	**AlMgSi1**
Tensile strength	310 MPa
Yield strength	240 MPa
Hardness	95 HB
Elongation	8-14 %
Elastic modulus	70,000 MPa

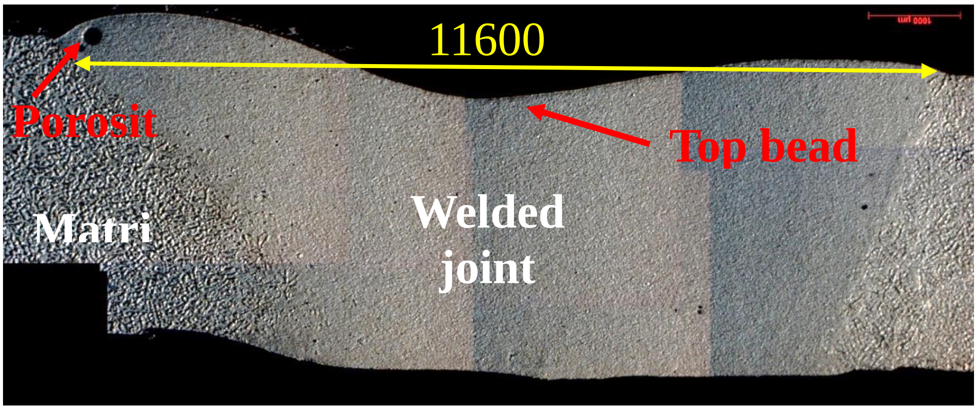
Results

In the following results, all cross-section views have been etched to create a visibly welded joint and matrix structure.

TIG

The welding was performed as a single-layer weld without a filler material to make it more comparable with other welding processes. The welded joint is homogenous, and no heat treatment zone is visible in the matrix (9). The diameter of the joint is 11.6 mm. The only weld defects are some little pores and a minimally sunken top bead.

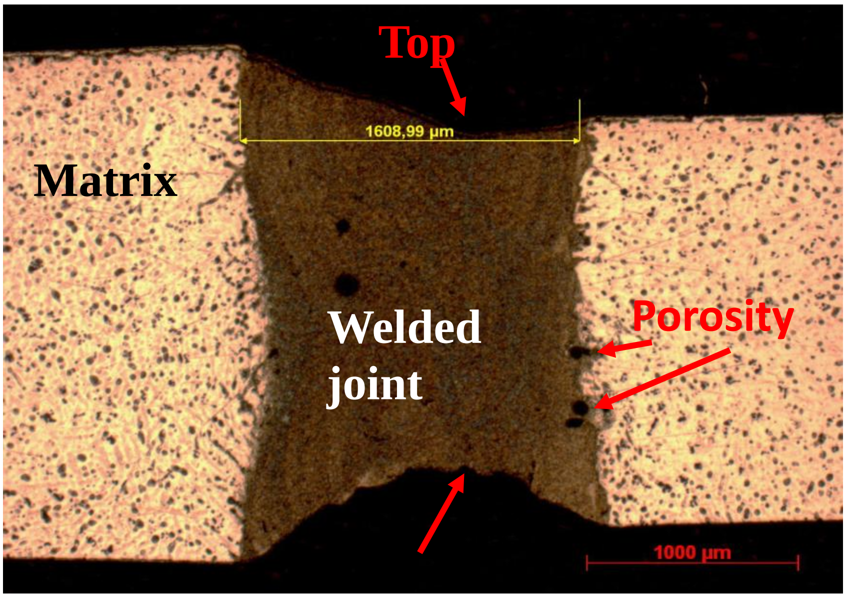
Figure 9. *Mg AM 60, TIG Welded Joint, No Filler Material, Cross-section View*



Laser Welding Process

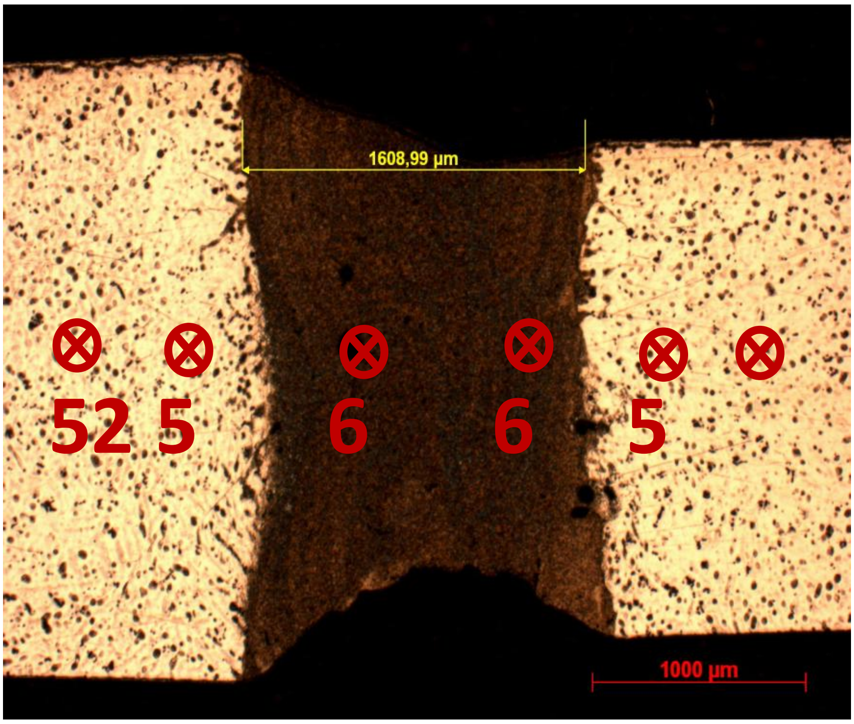
The laser welding shows similarities to the tungsten inert gas welding, but the weld joint diameter is just 1.6 mm. In order to be as near as possible to the real industrial applications, plates of different thicknesses were used.[10] Pores, a sunken top bead and a root defect can be seen in Figure 10. The pores are 50 percent smaller than the pores in the TIG welded joint.

Figure 10. *Mg AM 60, Laser Welded Joint, No Filler Material, Cross-section View*



Contrarily to TIG welding, no heat-affected zone appears. To check heat effects in and around the welded joint, Vickers hardness tests were performed. The results of the Vickers test can be seen in Figure 11.

Figure 11. *Mg AM 60, Laser Welded Joint, Vickers Hardness HV1, Cross-section View*

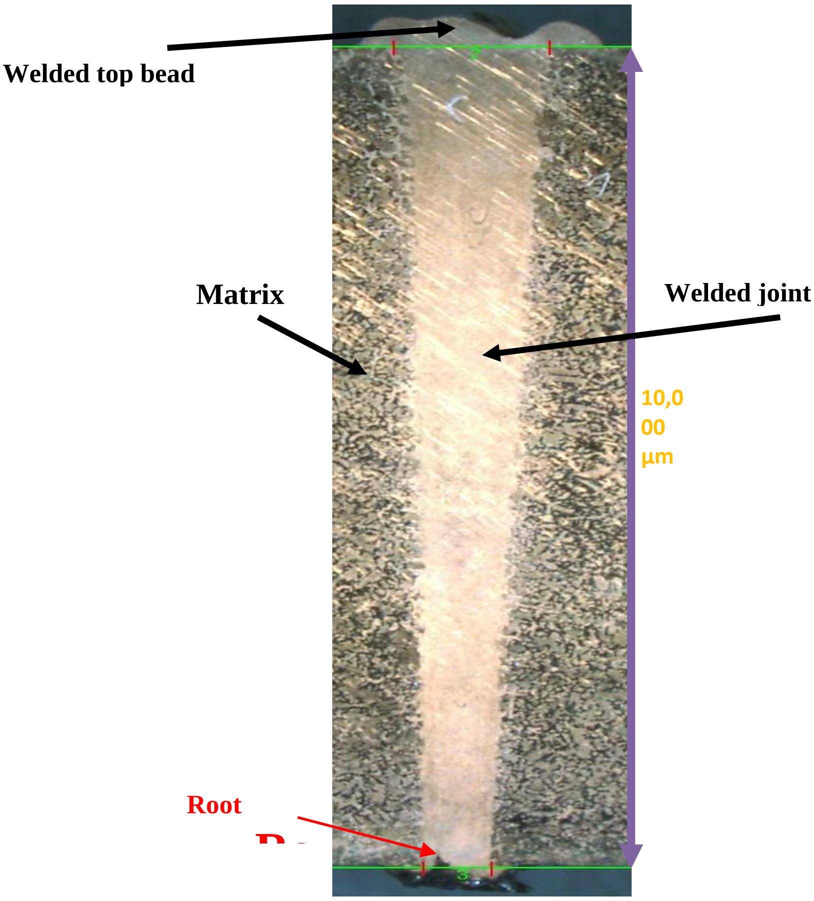


Electron Beam Welding

The electron beam welded joint has the smallest diameter of all welds with just 0.8 mm in width. As expected the electron beam weld shows no defects and forms a perfectly welded joint although the thickest material was used (Figure 13). Only a very small root defect is visible, but this could be caused by small differences in the thickness of the joining partners. The welded top bead can be seen in Figure 12, and neither shows considerable defects.[2]

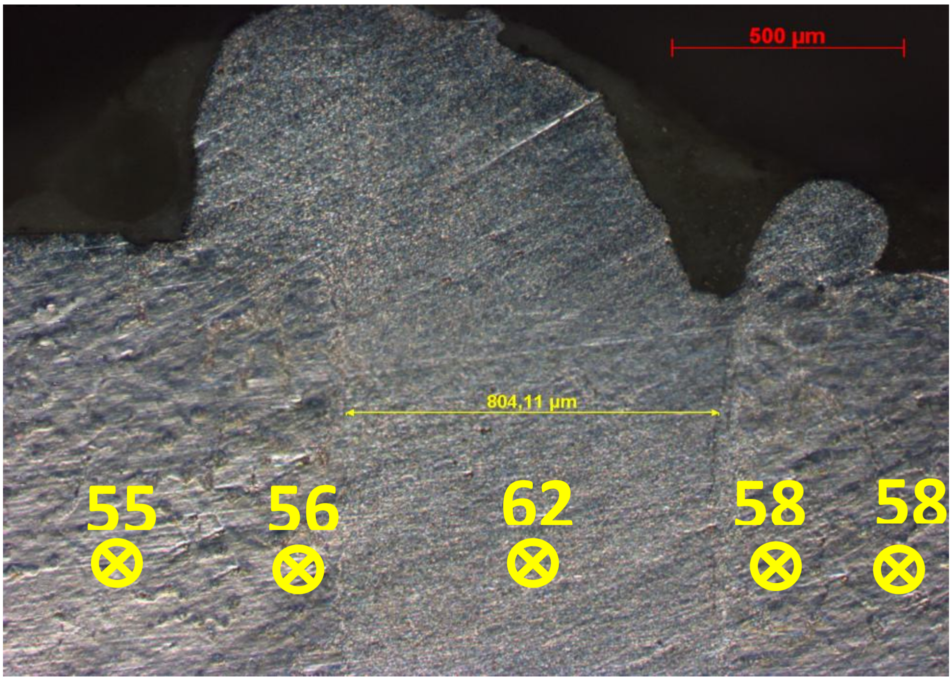
Figure 12. *Welded top bead, AM 60, No Filler Material*

Figure 13. *Electron Beam Welded Joint, AM 60, No Filler Material, Cross-section View*



To check hardening effects the hardness test by Vickers was used again. Results are shown in Figure 14.

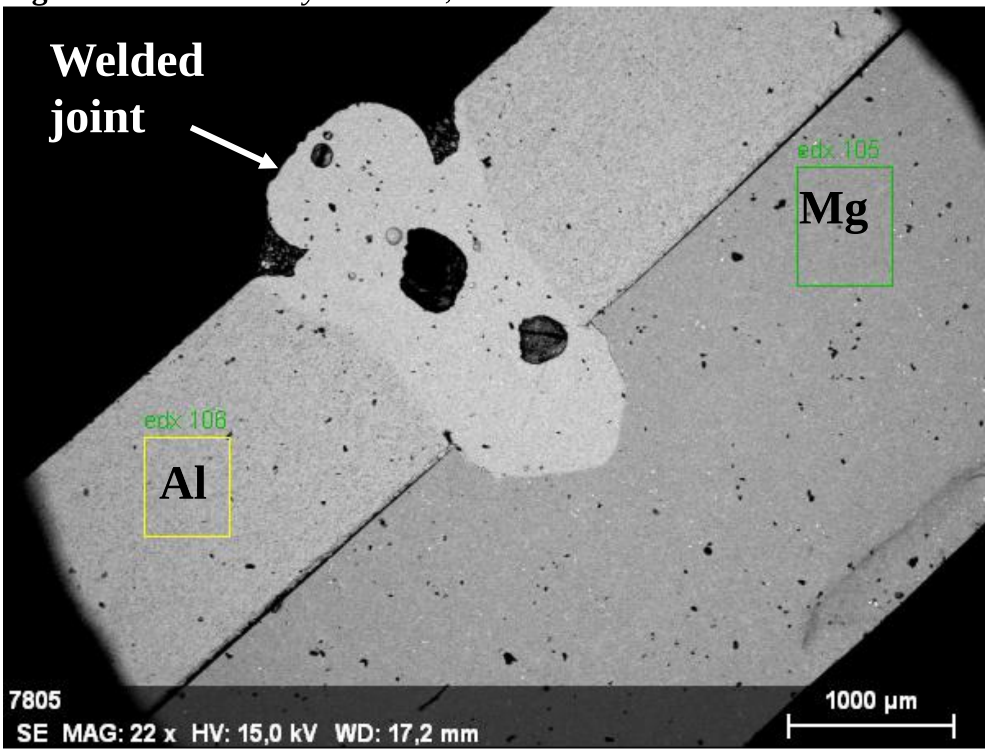
Figure 14. *Electron Beam Welded Joint, AM 60, No Filler, Vickers*



Hybrid Welding

To check the hybrid weld of magnesium/aluminium, an electron microscope was used. In the following figures, the brighter metal sheet is aluminium, the darker one is magnesium, and the welded joint is the bright zone in the middle of the aluminium (Figure 15). The big pores are directly visible (black coloured in all figures) in the welded joint. For a better analysis of the weld, energy-dispersive X-ray spectroscopy (EDX) was used. The EDX relies on a stimulation of a sample by x-rays. Every element has a unique atom structure, and the electromagnetic emission spectrum is also unique.

Figure 15. *Overview Hybrid Weld, Cross-section*



A so-called line scan shows the distribution in the welded joint (Figure 16). Due to the results of this line scan shown in Figure 17 (aluminium red, magnesium green), more tests have been performed. As it can be seen in Figure 17, the distribution of aluminium and magnesium varies over the weld. In the beginning of the scan, there is just aluminium as the scan started in the base material of aluminium. In the welded joint, a mix of aluminium and magnesium particles were identified related to a diffusion process of magnesium particles into the welded joint.[14] At the end of the weld seam, aluminium increases significantly, while magnesium decreases.

Figure 16. *Line Scan, Hybrid Weld, Cross-section*

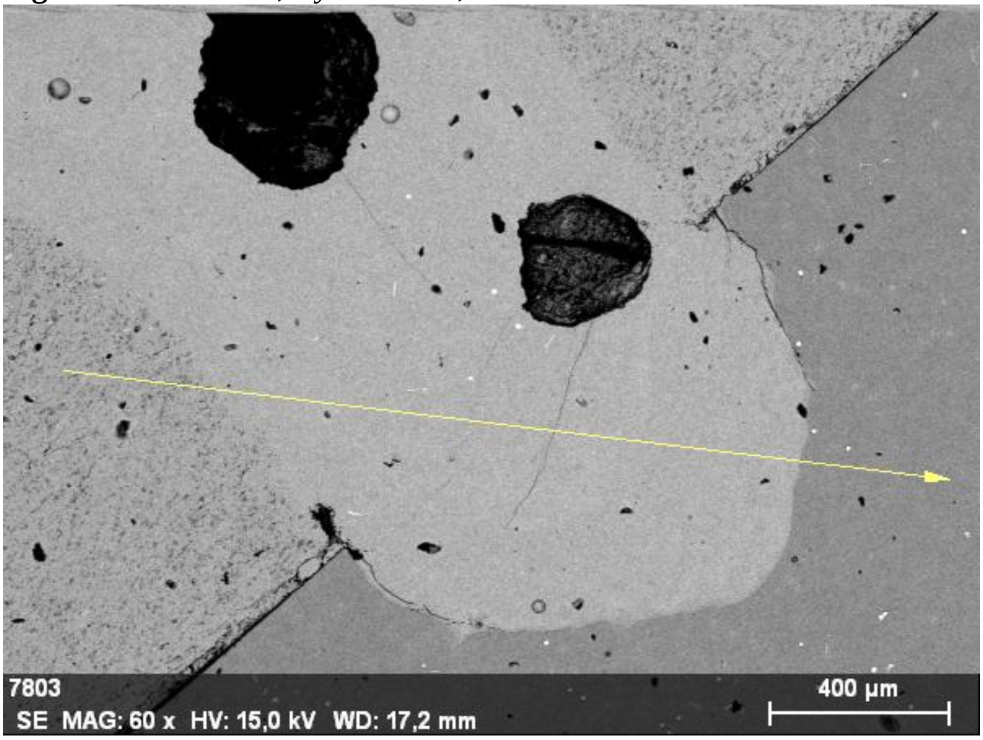
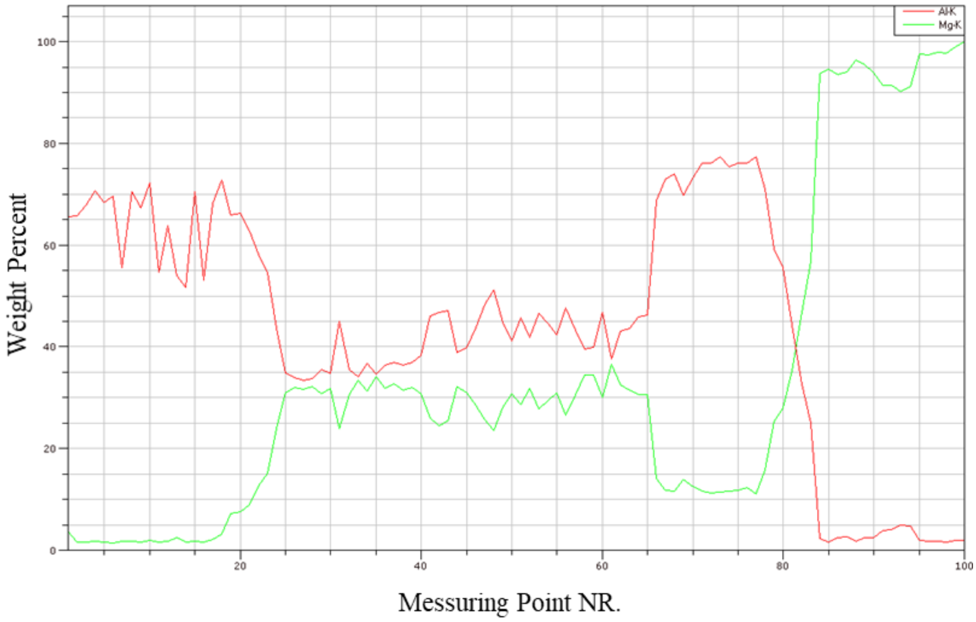


Figure 17. *Hybrid Weld, Element Distribution of the Line Scan (EDX)*



Supposable different intermetallic phases do exist in the welded joint. The distribution over the whole welded joint shows the increase of aluminium and is caused by an accumulation. The overview in Figure 18 and the hardness test by Vickers confirms this theory. The results of the hardness show that the aluminium alloy is softer than the magnesium because it needs heat treatment for hardening (Figure 19).

Figure 18. *Hybrid Weld, Distribution over the Whole Welded Joint and Heat Cracks*

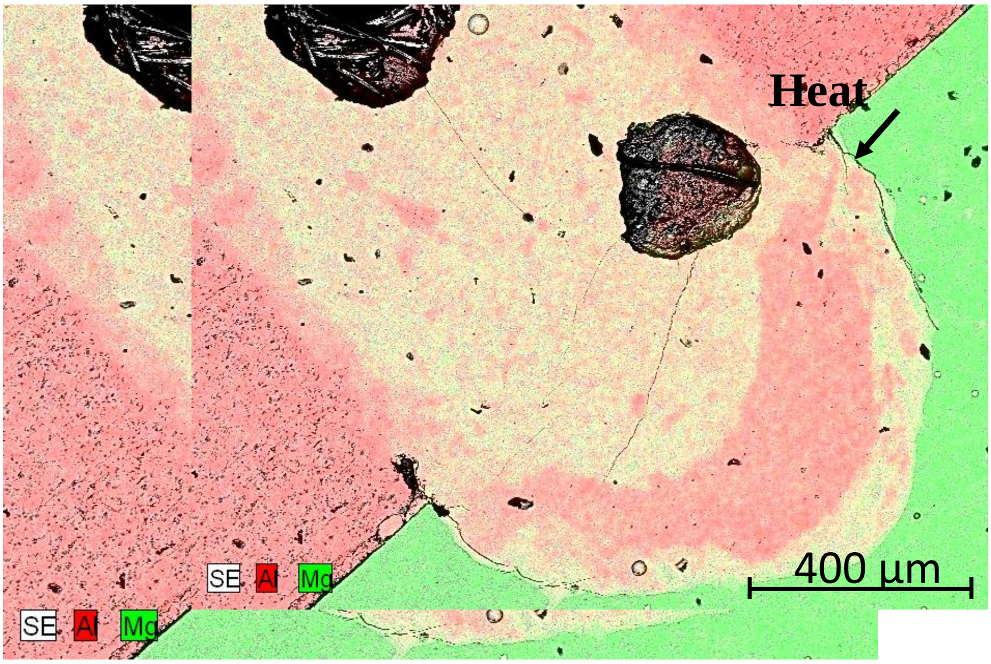
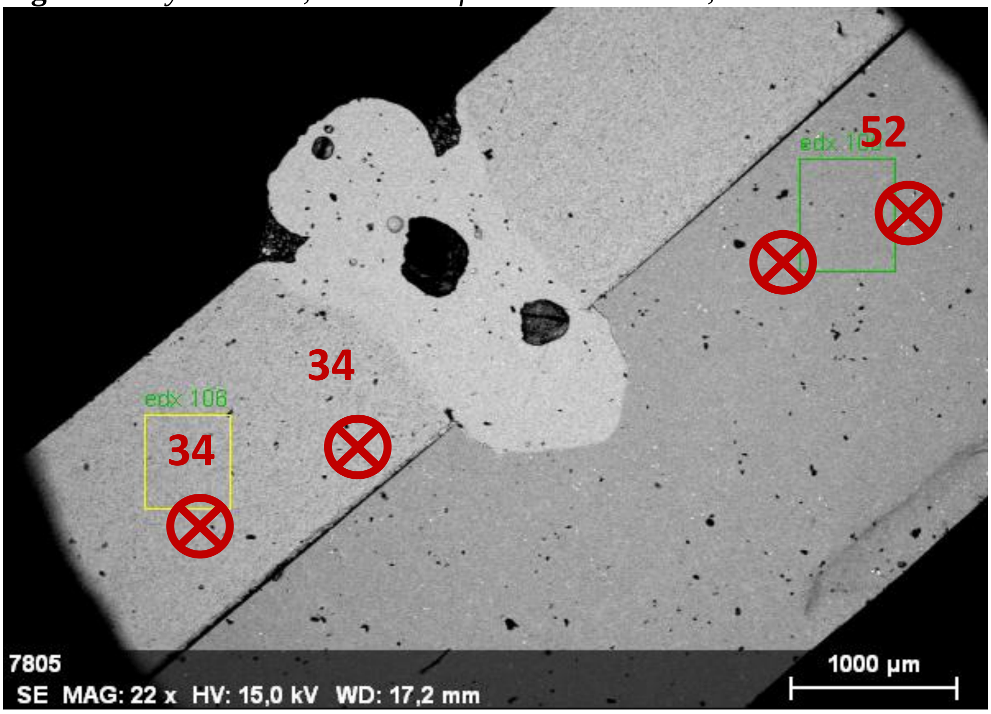
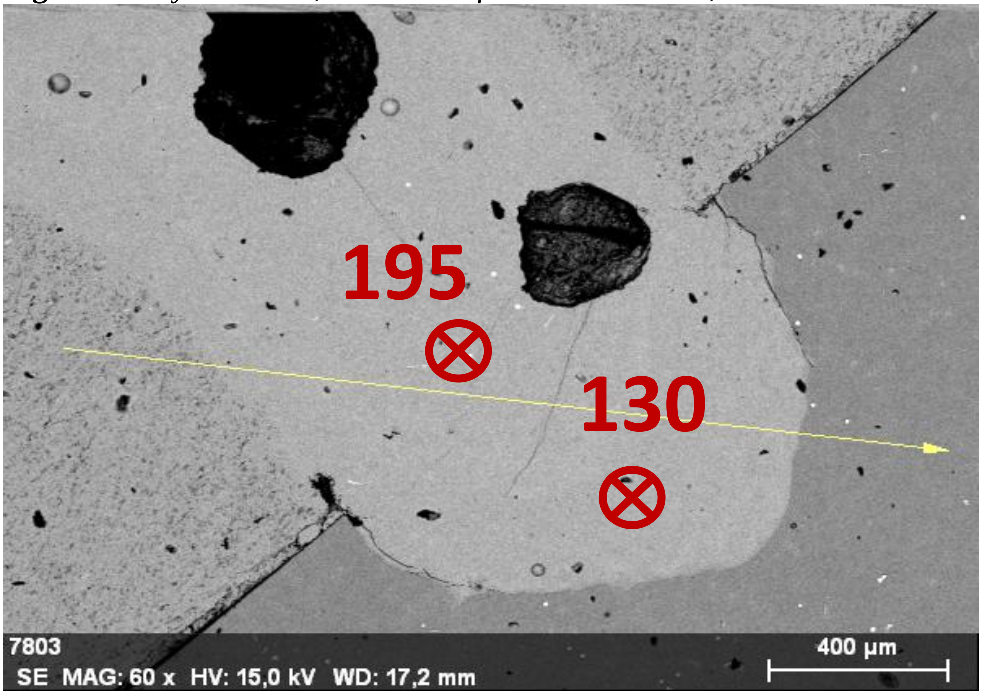


Figure 19. *Hybrid Weld, Hardness of the Base Materials, Cross-section View*



The welded joint itself has a higher hardness than the base materials (Figure 20). In the literature the intermetallic phases between aluminium and magnesium are described as very hard and brittle, so it can be stated that within the welded joint some intermetallic phases had been created, due to previous diffusion processes.

Figure 20. *Hybrid Weld, Hardness of the Welded Joint, Cross-section View*



To find an explanation of the examined results – the fact that the joint has a higher hardness - the Vickers test results were correlated with the phase diagram Mg/Al (Figure 21). The phase with a high percentage of aluminium (green cross, 135 HV) has a face-centred cubic lattice. The other phase with 195 HV (red cross) is settled near the so-called β-phase and is extremely brittle between aluminium and magnesium. Due to this effect, it has produced heat cracks between the welded joint and the magnesium base material (Figure 22).

Figure 21. *Distribution and Hardness of the Welded Joint*

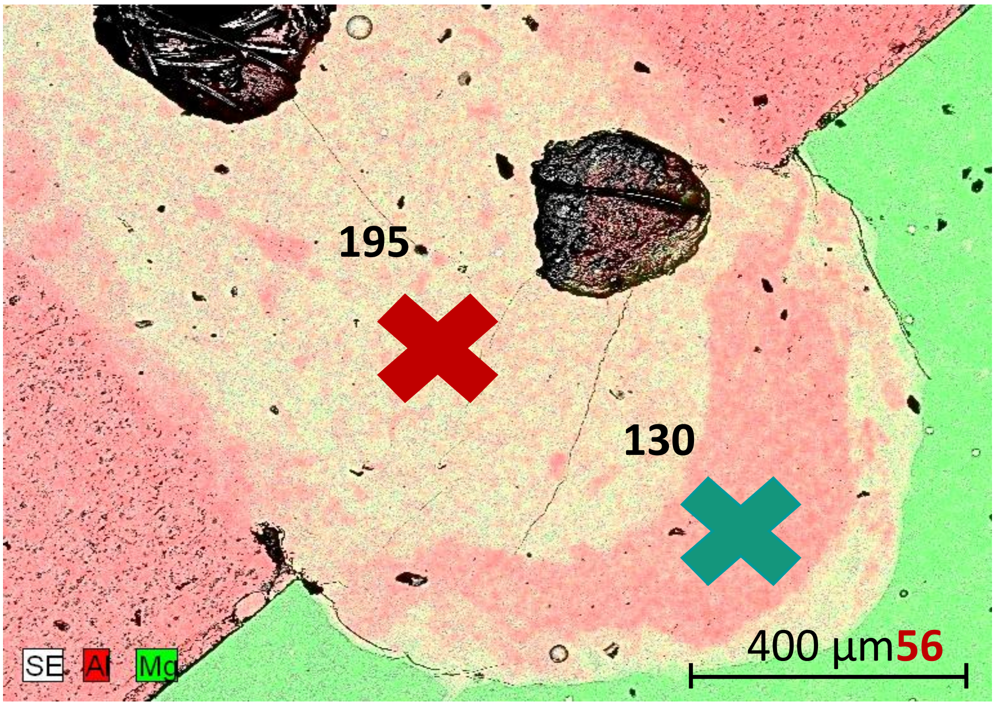
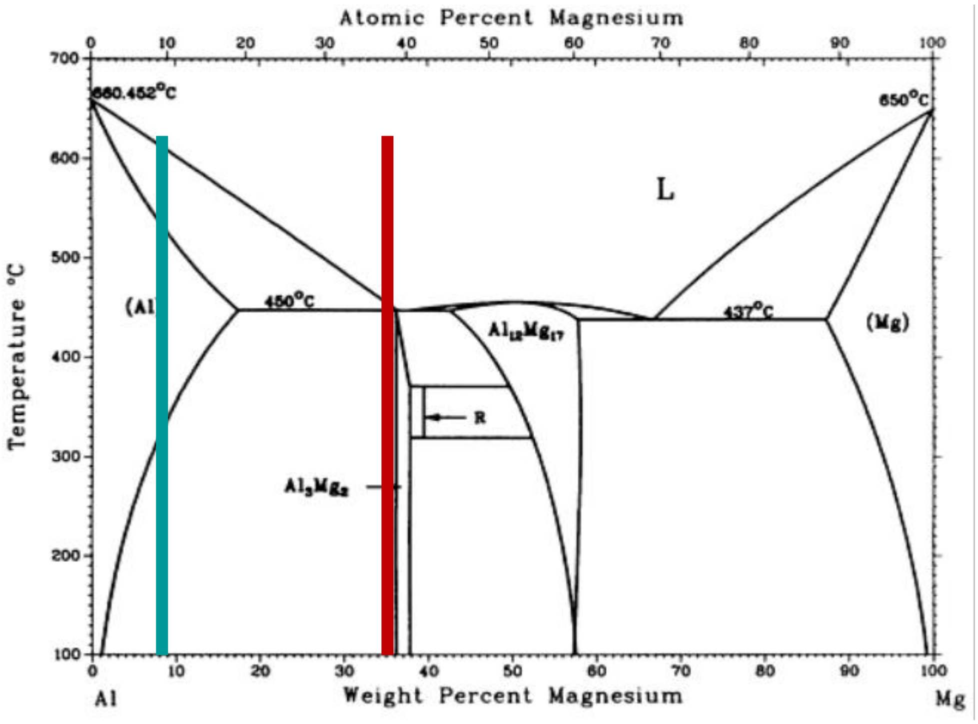


Figure 22. *Phase Diagram with the Selected Sections from Figure 21*



Discussion

At first, the tungsten inert gas welding will be observed. As already mentioned, the TIG welding is just an example to compare the newly tested processes with the most common one. In Figure 9, some little pores due to the small temperature range between the melting (650 °C) and boiling (1110 °C) point of magnesium were detected. The hardness tests by Vickers proved that no heat-affected zone was formed and no hardening of the welded joint is measurable, although there was a high heat introduction. The main drawbacks are the diameter of the welded joint with 11.6 mm and the warping effect. The warping effect caused a big problem, as the samples have to be fixed causing new problems such as internal stress and heat cracks. To minimize the internal stress, only one direction was blocked by fixation. In order to prevent the leaking of melted material and oxidation on the backside of the samples, an argon flooded weld pool was used. The results after these arrangements were satisfying, but they are not completely reproducible because of the influence of the welder. In opposition to the other tested processes, TIG welding was made manually, so the feed rate and the electrode distance are not constant. In the performed TIG tests, no filler material was used. Further researches will deal with the influence of different filler materials on the welding results.

The specimen for the laser beam welding (Figure 10) was made of different sheets due to the demand of many industrial applications to join parts of different thickness. This caused some problems, such as the sunken top bead and the root defect. The pores are similar to the pores in the TIG welding caused by the small temperature range between melting and boiling point. However, the pores in the laser welded joint are 50% smaller. As already expected, no heat-affected zone was formed because of the small heat treatment by the laser. The results of the Vickers hardness tests confirm that neither a heat-affected zone nor hardness increases in the welded joints were formed. The variation of the hardness that can be seen in Figure 12 in the welded joint is too low and can be disregarded. The diameter of the welded joint is 1.6 mm, nearly 10 percent of the diameter of the TIG welding. That effect is caused by the higher energy density of the laser beam. Therefore, a higher feed rate is possible due to a smaller heat treatment. The higher feed rate also accelerates the production time.

Electron beam welding joins the thickest sheets of all tests as it got the highest energy density of all processes. Although the sheets are 10 mm high, no important welding defects are visible, except a small root defect. That root defect was formed because the keyhole broke through the material and the vaporized metal leaked at the bottom of the material. Similar to the laser welding, neither a heat-affected zone nor a hardness increase of the welded joint appeared.[11] The Vickers hardness varies even less than in the laser beam welding. The electron beam welding is the only process that did not create pores caused by the high vacuum. However, the high vacuum is a disadvantage of the electron beam because the forming of the vacuum is time-consuming. Despite this, the results of the electron beam welding are the most satisfying ones. The connection of the matrix to the welded joint is nearly perfect, and no visible defects could be detected under the electron microscope.

The hybrid weld between magnesium and aluminum was the most complex test of all. In the Al/Mg phase diagram some different intermetallic phases are present. Some of these phases are very brittle, such as the β-phase, and should be avoided. Otherwise the welded joint is a predetermined breaking point. To vaporize as little as possible, the focus point of the laser beam was on the aluminum, which has a thicker oxide-layer and a larger range between its melting and boiling points. However, this could not solve the diffusion of the magnesium into the aluminum and therefore the creation of different intermetallic phases.[12, 13] Caused by the results of the EDX and the Vickers hardness, two different phases could be identified. One of these phases can be determined to be the β-phase (Al_3Mg_2) with regard to the high hardness and the percentage of aluminum. The other phase is aluminum with β-phase dispersions on its grain boundaries. The reason for the conglomerate of aluminum at the borders of the welded joint is still unexplained and needs more research. It might be explained by the oxide-layer of aluminum that has a much higher melting point than magnesium. The heat transfer of the oxide-layer could be sufficient to melt the magnesium before it melts itself. Other weld failures, such as the pores or the heat cracks, can be explained. The pores are results of the keyhole that was formed by the laser beam and can be prevented by optimizing the weld parameters. The heat cracks are caused by the different heat treatments of both metals and the intermetallic phases. They could be prevented by using controlled heat treatment or even smaller cooling rates.

Conclusions

The results show that different welding processes for magnesium are possible. In addition to the WIG process, laser welding and EB welding techniques have been examined. Electron beam welding gives the best results with regard to a welded joint free of defects, even by welding plates of different thickness. However, the EB-process is cost-intensive and not suitable for mass production. This is in opposition to laser welding. The tungsten inert gas welding is the most common welding technique used for magnesium, and the results are moderate. With regard to complex welding problems from high heat input, well-educated welders are required. Comparing all three techniques, laser welding could be the most interesting technique. The results of the magnesium-magnesium weld are respectable and the production time is remarkable. Besides that, lasers are already used in existing supply chains for many industrial applications. However, some more efforts for optimizing the laser parameters have to be managed. The first test results predict welded joints without defects. The welding researches of hybrid materials like Mg/Al indicate a wide range of unsolved problems. To avoid the presence of brittle intermetallic phases, an optimized process of engineering is demanded. In the near future, the importance of magnesium for industrial applications will grow continuously. Newly developed magnesium alloys in common with new joining techniques will pave the way for new possibilities.

References

[1] Horst E. Friedrich, Barry L Mordike, 2006, Springer-Verlag Berlin Heidelberg, Magnesium Technology Metallurgy, Desing Data, Applications.
[2] Günter Schulze, 2010, Springer-Verlag Berlin Heidelberg, the metallurgy of welding.
[3] Hajo Dieringa, Klaus Drechsler, Thomas Evertz, Volker Flaxa, Peter Furrer, Rainer Gadow, Zacharias Georgeou, Rudolf-Hermann Gronebaum †, Karl Ulrich Kainer, Norbert Kwiaton, Christian Lesch, Christoph Leyens, Andreas Müller, Manuel Otto, Manfred Peters, Joachim Schöttler, Thomas Schulz, Bianca Springub, Gerald Widegger, Gerhard Ziegmann, 2017, Springer Fachmedien Wiesbaden GmbH, Leichtbauwerkstoffe [Lightweight materials].
[4] Cao, X., Jahazi, M., Immarigeon, J. P., & Wallace, W. (2006). A review of laser welding techniques for magnesium alloys. Journal of Materials Processing Technology, 171(2), 188-204.
[5] Zhao, H., & DebRoy, T. (2001). Pore formation during laser beam welding of die-cast magnesium alloy AM60B-mechanism and remedy. Welding Journal, 80(8), 204-210.
[6] Alfred Herbert Fritz und Günter Schulze, 2015, Springer-Verlag Berlin Heidelberg, Fügen, ISBN 978-3-662-46555-4.
[7] Czerwinski, F., 2011, Magnesium Alloys-Design, Processing and Properties, InTech, Welding and joining of magnesium alloys.
[8] DIN EN 573, 2009, Aluminium and aluminium alloys.
[9] Weisheit, A., Galun, R., & Mordike, B. L., 1998, WELDING JOURNAL-NEW YORK 77-149-s, CO_2 Laser Beam Welding of Magnesium-Based Alloy.

[10] Marc Schiry, 2015. Laserbeam welding of dissimilar materials at the example of hard metal and steel, Master Thesis 2015, University of Applied Sciences, Trier.

[11] Quan, Y. J., Chen, Z. H., Gong, X. S., & Yu, Z. H. (2008). Effects of heat input on microstructure and tensile properties of laser welded magnesium alloy AZ31. Materials Characterization, 59(10), 1491-1497.

[12] Zhao, H., & DebRoy, T. (2001). Pore formation during laser beam welding of die-cast magnesium alloy AM60B-mechanism and remedy. Welding Journal, 80(8), 204-210.

[13] Wahba, M., Mizutani, M., Kawahito, Y., & Katayama, S. (2012). Laser welding of die-cast AZ91D magnesium alloy. Materials & Design, 33, 569-576.

[14] Borrisutthekul, R., Miyashita, Y., & Mutoh, Y. (2005). Dissimilar material laser welding between magnesium alloy AZ31B and aluminum alloy A5052-O. Science and Technology of Advanced Materials, 6(2), 199-204.