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MAGNESIUM ALLOY WELDING: NEW EXPERIENCES

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ABSTRACT

In the automotive business, lightweight constructions are playing a bigger role. Given this, some structural components in these industrial portions will be made of magnesium, a lightweight metal. In comparison to their weight, magnesium alloys have mechanical characteristics that are generally acceptable. A large number of pieces may be manufactured because casting magnesium is a well-known process. Screwing techniques are used to attach magnesium components. Bolting connections have the drawback of being expensive and occasionally subject to corrosion. Optimized joining processes are necessary for magnesium components to be built with greater flexibility. Only a relatively small amount of knowledge is now required to fuse these magnesium alloys together.

Keywords:lightweight,Welding,Magnesium,Alloy

1.INTRODUCTION

One of the most prevalent and lightest substances on the planet is magnesium. Due to the demand for lightweight constructions, magnesium is becoming more and more important in production. The automotive industry and other sectors are forced to come up with innovative approaches due to increased environmental restrictions. Aluminum and other light metals are widely used in modern automobiles. Weight reduction is also possible with composite materials like carbon or glass fibres, but they are expensive and challenging to process once formed. Industrial applications therefore require as quick and inexpensive a production process as possible. Casting is a method that can be used to create new magnesium alloys in large quantities for a variety of applications. the upgrading of current aluminum trusses. Magnesium was historically only utilised for invisible structures like gearbox covers, lower

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seat structures, or dashboard structures because to its high material costs and moderate corrosion qualities. In actuality, the only use for magnesium as a building material that the majority of people think of is a pencil sharpener. When the teacher describes the earth alkali metals and their high reactivity with a burning magnesium wire, some people could recall their chemistry lessons. Despite the fact that a solid piece of magnesium is difficult to ignite, even with a Bunsen burner, this may be the reason why some operators are reluctant to use it without cooling or welding it.

Due to their high costs, magnesium wrought alloys gave the metal a bad reputation in the industrial world. The hexagonal lattice also limits their formability to a certain extent. Newly created wrought alloys and manufacturing techniques increase the appeal of new application possibilities, such shell constructions. Additionally, the cost factor has been reduced, resulting in a minimal price difference between aluminium and magnesium.

Only by linking components or assemblies are complex constructions feasible. As a result, there is a greater need for better connecting techniques. The rise in aluminium constructions over the past several years was made feasible by joining methods that have been proven effective in the field. These days, glue, screws, or bolts are used to assemble magnesium components. Applying different joining technologies should change this since it restricts the range of applications. New welding techniques for magnesium can lead to new opportunities. In the future, hybrid welding using magnesium will also be quite important. Within the next several years, it can be anticipated that the economic use of such hybrid joins will estimate material technology. [1, 2, 3, 4, 5].

Difficulties in Welding Magnesium Alloys

Due to its numerous similarities to aluminium, including the existence of the oxide layer, welding magnesium is challenging. Although considerably thinner than aluminum's oxide layer, magnesium also generates one on its surface, which results in the same issues. Because the shift in polarity breaks the oxide layer, tungsten inert gas welding requires an alternating current (AC). However, The oxide layer stabilises the welding arc, thus it shouldn't be mechanically removed. As soon as the layer melts, the high amount of energy required to shatter it results in new issues. Because the base material beneath the surface has a lower melting point than the oxide layer and is otherwise too liquid, the energy rate must be decreased (Figure 1).

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).

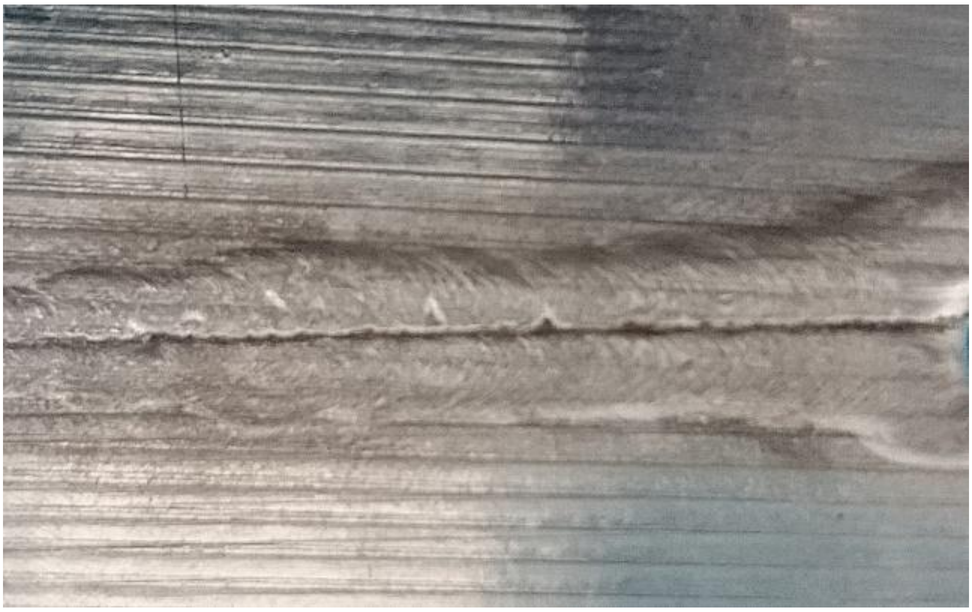

Figure 2. *Mg AM 60, TIG-welded, Oxidation on the Backside*

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.

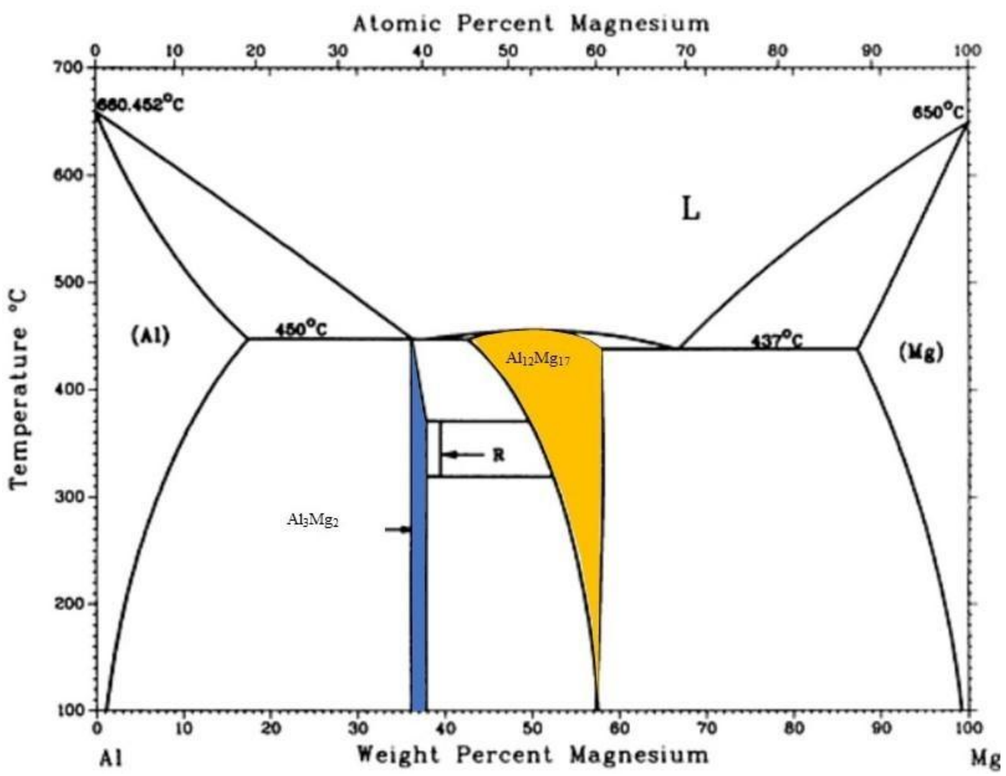

Figure 3. *Phase Diagram Al/Mg, Intermetallic Phases*

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.

2.LITERATURE REVIEW

Manufacturing Process

Magnesium and its alloys combine low weight with affordable manufacture, as was already established. Magnesium can be used in pressure die casting to benefit from characteristics including high casting rates, net forms, and long die life.

Melting metal is fed into a steel die during die casting, then the steel die is quickly cooled. High-pressure die casting seeks to reduce the amount of time required for each component. Additionally, it has the special capacity to shape the injected molten metal into an exact measurement and smoothly finished form.

Capabilities for Welding Magnesium

In order to reduce weight, lightweight constructions are becoming more and more crucial. Additionally crucial is the modernization of joining methods. Components are fastened with screws or bolts in modern magnesium casts, but this is expensive and takes a lot of manufacturing time. For the best possible material use, the integration of die cast assemblies, for instance in the automotive industry, calls for new joining techniques. Furthermore, since screws and bolts are frequently composed of different materials like titanium, steel, or aluminium, joining with them creates new issues. The varying thermal expansion of the materials is one of the issues. At 25 °C, iron expands at a rate of 11.8 m/(m•K) while magnesium expands at a rate of 24.8 m/(m•K).

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 stands for tungsten inert gas welding, which was first developed in 1936 as so-called "argonarc" welding in the United States. The method was first only applied to premium materials or specific purposes. TIG welding is one of the most used welding methods today and may be used with almost any metal. Its excellent welded connection with a low heat transfer in the base material is the cause of its wide dissemination. 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].

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Laser Welding

Light Amplification by Stimulated Emission of Radiation, or laser, is the abbreviation. Similar to how a loupe concentrates sunlight, a laser transfers heat through focused light. The utilised spectrum distinguishes laser light from sunlight; whereas laser light normally has a smaller band of wavelengths, sunlight occurs in a wide spectrum. Different laser types create wavelengths that are unique. The medium that produces the initial differentiation transmission of light. Different types of lasers, including gas, dye, metal-vapor, solid-state, and semiconductor lasers, are employed today. A solid-state disc laser was used for our investigation. A diode pumped solid-state laser known as a disc laser, or active mirror laser. They are referred to as "pumped lasers" because the gain medium creates the disc . 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].

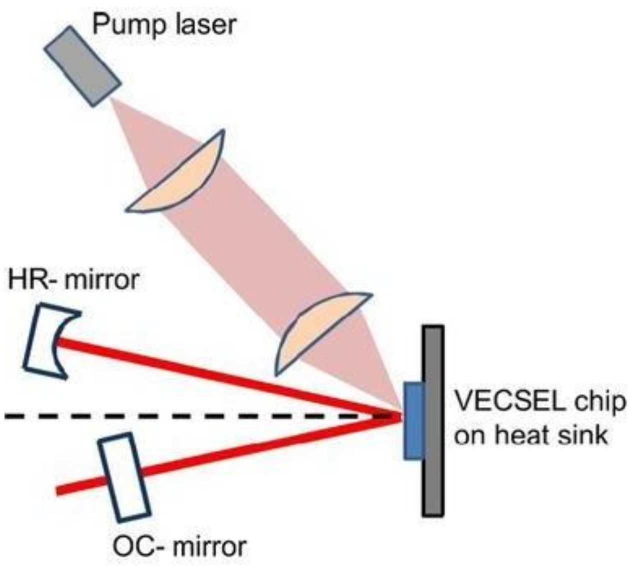

Figure 4. *Functional Principle of a Disk Laser*[10]

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

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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 Figure5.

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].

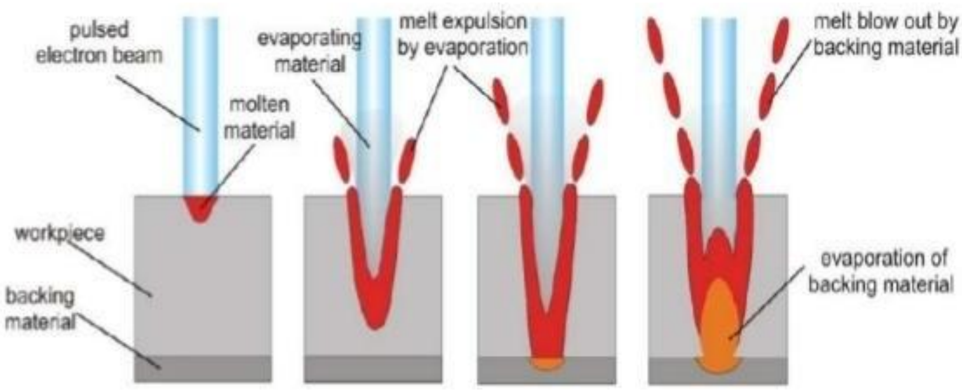

Figure 5. *Functional Principle of the Joining Process by EBW*

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Used Materials

Magnesium

Sir Humphrey Davy discovered and first separated metal magnesium in 1808. But it took more than a century before it was used for the first time as a building material. Due to its low density, magnesium had its real breakthrough during World War II as one of the primary metals used in aeronautical construction. The annual production peaked in 1944 at 228 kt. Production fell off after the war until the late 1980s. Magnesium was rediscovered at this period as a building material. The benefit of weight reduction led to the use of magnesium, and the lightweight idea is still relevant in almost every industry today. Carbon composites are almost as dense but far more expensive and challenging to deal with. Even aluminium weighs 30% more than magnesium.

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)

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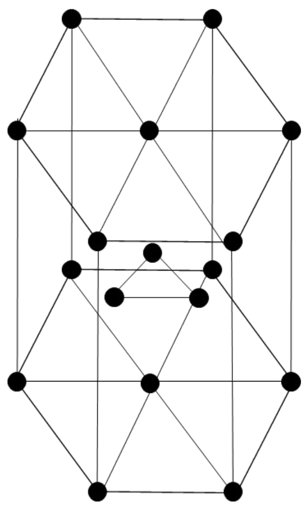

Figure 6. *Magnesium Unit Cell*

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

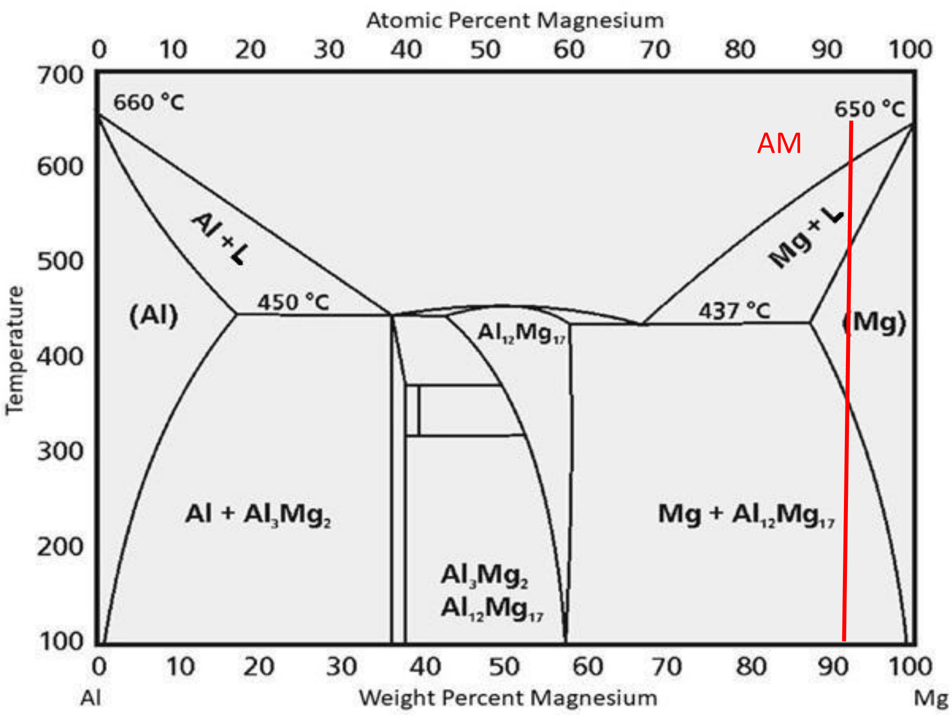

Figure 7. *Magnesium-Aluminium Phase Diagram*

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)

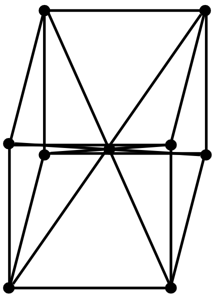

Figure 8. Aluminium Unit Cell[6]

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

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3.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.

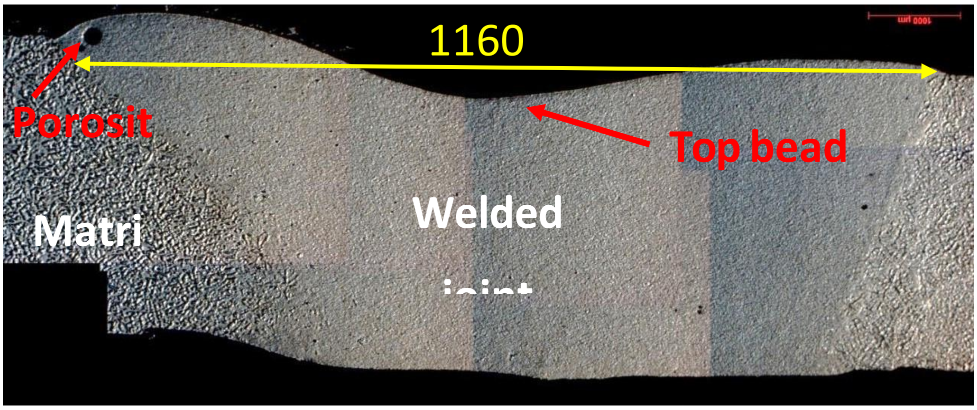

Figure 9. *Mg AM 60, TIG Welded Joint, No Filler Material, Cross-section View*

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. Contrarily to TIG welding, no heat-affected zone appears. To check heat effects in and around the welded joint, Vickers hardness tests were performed.

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*

Welded top bead

Matrix

Welded joint

10,0

00

µm

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

Root

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

55 56 62 58 58

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.

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

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into the welded joint.[14] At the end of the weld seam, aluminium increases significantly, while magnesium decreases.

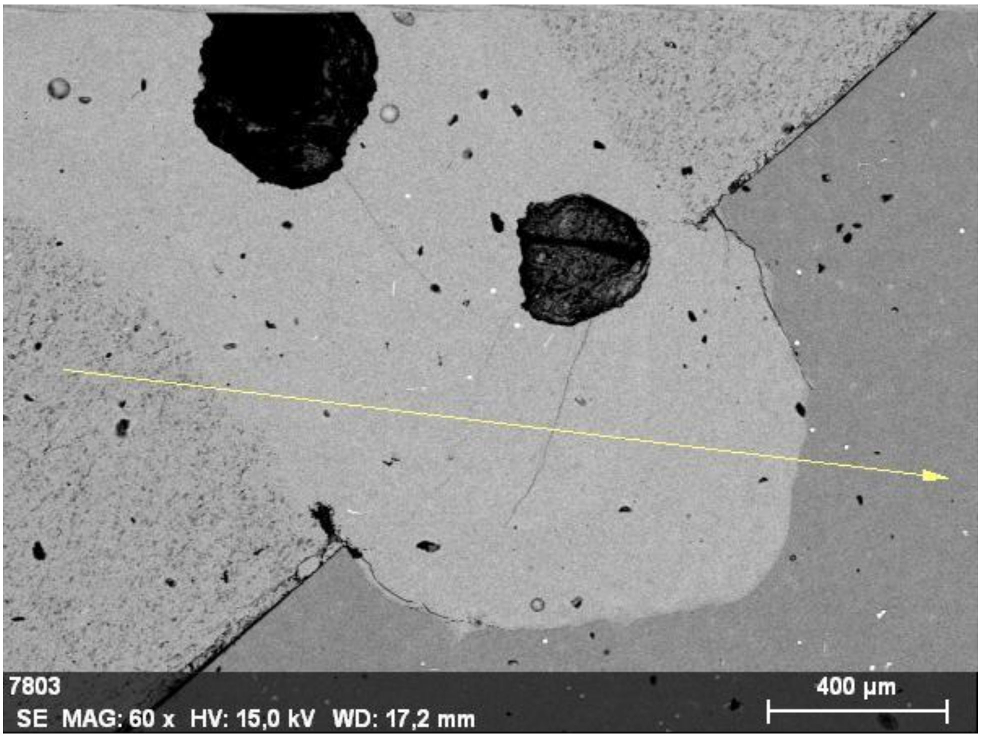

Figure 16. *Line Scan, Hybrid Weld, Cross-section*

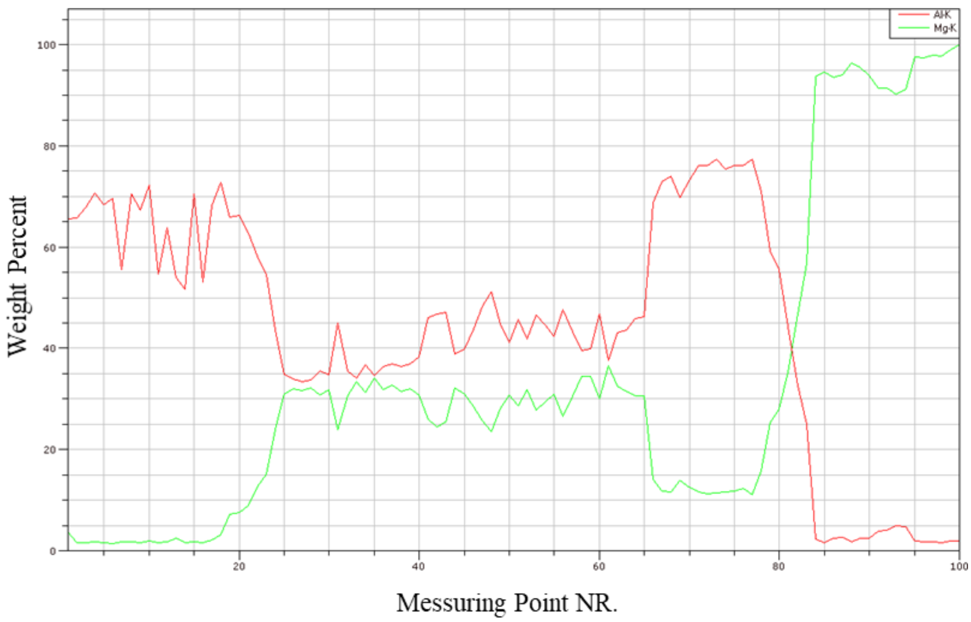

Figure 17. *Hybrid Weld, Element Distribution of the Line Scan (EDX)*

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

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of the hardness show that the aluminium alloy is softer than the magnesium because it needs heat treatment for hardening (Figure 19).

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.

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).

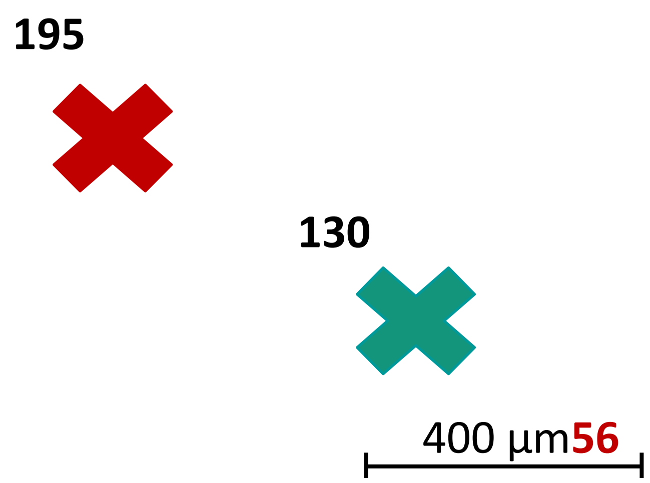

Figure 21. *Distribution and Hardness of the Welded Joint*

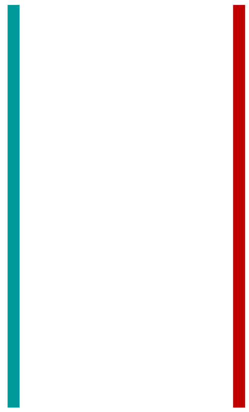

Figure 22. Phase Diagram with the Selected Sections from Figure 21

3.DISCUSSION

We shall first watch the tungsten inert gas welding. TIG welding is simply one example used to contrast recently tested processes with the most popular, as was previously noted. Due to the narrow temperature range between the melting point of magnesium (650 °C) and boiling point (1110 °C), some tiny pores were found in Figure 9. Despite the significant heat introduction, the Vickers hardness tests showed that no heat-affected zone had formed and that there had been no discernible hardening of the welded junction. The biggest drawbacks are the warping effect and the 11.6 mm diameter of the welded joint. The samples had to be fixed because of the warping effect, which created new issues like internal stress and heat.

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.

4. CONCLUSIONS

The results show how flexible magnesium welding techniques are. In addition to the WIG approach, other welding techniques like laser welding and EB welding have also been studied. Even when welding plates of different thicknesses, electron beam welding results in the best-looking, flawlessly welded junctions. However, the EB-process is expensive and not suited for mass production. This is not laser welding. Tungsten inert gas welding, the most common method of welding magnesium, produces acceptable results. For complicated welding problems involving a lot of heat input, educated welders are required. Laser welding may be the most exciting of the three techniques. The outcomes of the magnesium-magnesium weld are satisfactory, and the manufacturing time is appropriate.

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