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Exploring the Benefits and Limitations of Wire-based Direct Energy Deposition of Magnesium Alloys

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Abstract

Metal additive manufacturing (AM) processes enable the production of complex, near-net-shape structures designed for low weight. When combined with light materials, such as magnesium, component weight can be further optimised. While powder-based AM processes have several limitations, wire-based processes circumvent many of these drawbacks. In this paper, we review the advantages and disadvantages of different AM processes used for magnesium and present the results of simple test geometries fabricated using waDED (wire-based direct energy deposition). We also assess how high-performance parts can be produced within a short lead time and without the need for tooling.

1. Introduction

Magnesium (Mg) alloys offer a unique combination of properties that make them interesting for aviation and space applications: Low density (< 2 g/cm³), high specific strength and stiffness. By using light materials like Mg in space applications, the overall vehicle weight can be decreased, leading to reduced fuel consumption, increased payload capacity and therefore lower operation costs. Another advantage of Mg is its reactivity, which causes the material to thermally disintegrate upon re-entry into the Earth's atmosphere, preventing fragments from reaching the surface.
Mg can be processed by a wide range of methods: In addition to classical casting and forming, excellent successes have also been achieved with additive manufacturing (AM) in recent years. Most AM processes use powders as starting materials, e.g., laser powder-bed fusion (L-PBF) and selective laser sintering (SLS). However, the possible part sizes are typically limited to << 1 m, as the processing chamber is subject to size limitations and building speed is comparably low [1]. Another major problem of powder-based processes using Mg is the feedstock itself: Mg powder is very reactive, which makes handling challenging. Furthermore, Mg powder production is complex and high safety standards must be maintained, which makes it costly and hardly available in sufficient quantities.

By using wire-based AM methods, these disadvantages can be greatly reduced: The production of Mg wire from cast material is straightforward and the wire itself can be handled without any safety hazard. Wire manufacturing speeds are much faster compared to powder production and the equipment necessary is cost-efficient and widely available. However, the main advantage of wire-based AM lies in the part building process itself: As the part production does not need an enclosed chamber, the possible part size that can be produced is nearly unlimited. At the same time, deposition rates when using Mg can reach values of 1 kg/h and higher, depending on the used wire diameter [2]. In addition, commercial welding equipment can be used, increasing flexibility, and providing a cost-effective process without high investment.
Particularly in the case of large-volume components, the process represents a clear advantage over conventional production methods, as no molds are required, and high quality can be ensured over the entire volume of the component. Additionally, in comparison to subtractive methods, e.g., milling, no large volume feedstock is necessary. Nevertheless, there are also limitations: the representable resolution and complexity of the parts are comparatively low and, in most cases, post-processing by mechanical machining is required. Furthermore, strength-increasing measures such as grain refinement and work hardening are difficult or impossible to implement.

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In this paper, we present a brief comparison of different AM processes for Mg, addressing the differences between powder- and wire-based processes. The wire-arc direct energy deposition (waDED) process is shown in detail and its advantages and limitations are discussed. Furthermore, microstructure and mechanical properties of waDED parts made from AZ61 [3], AX13 [4], AZ91CaY [5] and MX1 are summarized.

1.1 Powder-based additive manufacturing (AM) processes for magnesium

The following section gives an overview of powder-based additive manufacturing methods for magnesium alloys.

<u>Laser-powder bed fusion (L-PBF)</u>

In the laser-powder bed fusion (L-PBF) process, a thin layer of metal powder is applied to a substrate plate (build plate), placed inside an enclosed fabrication chamber. A high-powered laser melts the metal powder and fuses the individual particles into shape. After the first layer is fused, a new layer of powder is applied, and the process is repeated until a three-dimensional part is formed. As each previous layer provides a base for the next material to be applied, complex freeform shapes, including overhangs and cavities, can be achieved. Typical powder diameters used are < 70 µm and layer thicknesses are approx. 20-100 µm, allowing the production of lightweight, complex structures in net-shape/near-net shape [6], [7]. Figure 1 shows a schematic representation of the laser-powder bed fusion process (fabrication chamber omitted).

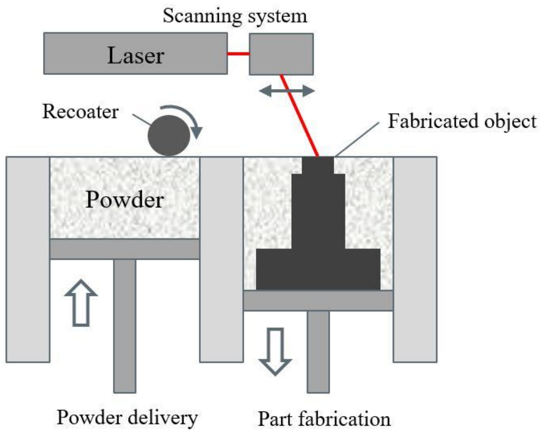

Figure 1: Schematic representation of the laser-powder bed fusion (L-PBF) process, based on [8]

The disadvantages of the process are the same as for the other powder processes, i.e., powder handling, limited part size and low building rates. The high temperatures generated by the laser cause Mg to vaporise in the fabrication chamber and the resulting fumes reduce the laser's efficiency. To reduce the negative effect of the Mg fumes, an inert gas stream is directed over the powder bed. The combination of evaporating powder and individual particles blown away by the shielding gas stream leads to microporosity in the manufactured parts [9], [10]. Additionally, as solidification takes place under non-equilibrium conditions, microstructural features such as elongated grains, cracks, pores and anisotropic mechanical properties are common [11], [12]. Nevertheless, Mg parts produced via L-PBF often show similar or even higher mechanical properties compared to conventional processes such as casting, resulting from the small volume melt pools and resulting high solidification rates [13].

<u>Binder-jetting</u>

In binder jetting, the components are built up layer by layer by applying metal powder to a build plate and bonding them together, similar to L-BPF. Instead of a heat source, the individual particles are bonded together with the aid of an applied polymer-based binder [14]. A schematic representation of the binder jetting process is given in Figure 2. After completion of the printing process, the excess powder and the remaining binder are removed, and the component is finished by a heat treatment (sintering process). Since the powder sizes and materials used are comparable to those of the L-PBF process, the possible part complexity is also comparable. Advantages of the binder-jetting process over

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L-PBF are the operation under ambient conditions and possibility to fully recycle the used powders [15]. A disadvantage, however, is the typically lower achievable mechanical strength due to the higher porosity.

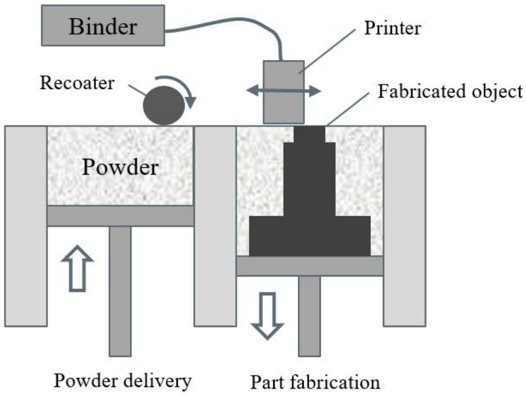

Figure 2: Schematic representation of the binder jetting process, based on [16]

Powder directed energy deposition (pDED)

In powder directed energy deposition, powder material is fed into a nozzle, where a focused energy source, typically a laser, electron beam or plasma arc, is used to melt the powder. Subsequently, the molten material is deposited layer by layer to the base material or build plate to form the part. A schematic representation of the process is given in Figure 3. While the possible part size is usually larger compared to binder jetting and L-PBF, the achievable part complexity and surface quality is typically lower [1]. As the powders used are typically larger in diameter than those used in the other two powder AM processes described, deposition rates are higher (up to 10 times compared to L-PBF) while the powders are generally cheaper [17].

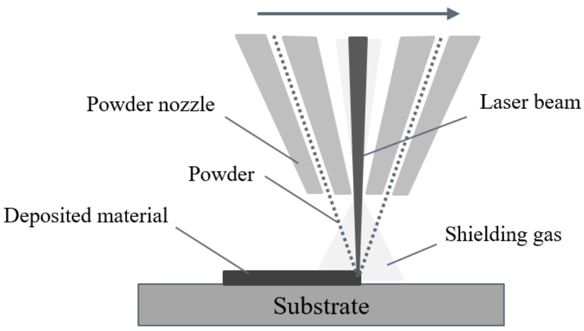

Figure 3: Schematic representation of the pDED process, based on [18]

1.2 Wire-arc direct energy deposition (waDED) of magnesium

In the wire-arc direct energy deposition process, wire material is molten by a heat source (electric or plasma arc) and deposited layer by layer until the part is finished. The equipment used for waDED with electric arc melting is very basic and main components comprises of a power source, a wire-feeder, and a welding torch. Additionally, a robot arm for part handling and another for guiding the welding torch can be used, increasing the achievable part complexity. As the welding torch typically includes a local gas shielding, preventing oxygen from entering the molten pool, an enclosed fabrication chamber is not necessary. Wire-based AM processes are generally much easier and cheaper to use than powder-based processes, as there is no need to handle highly reactive powders and the used equipment is cost-effective. Compared to powder-based processes, wire-based systems have significantly higher productivity and lower costs. Additionally, part size is unlimited and the buy-to-fly ratio is very high compared to subtractive methods and most competing additive manufacturing methods [19]. However, the possible component complexity is lower and the wall thicknesses that can be produced are higher when compared to powder AM processes. This makes wire-based additive processes mainly suitable for large components with low to medium complexity. Compared to casting, the

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waDED process is superior especially for small quantities of large components with high demands on mechanical stability. Figure 4 shows a schematic representation of the waDED process.

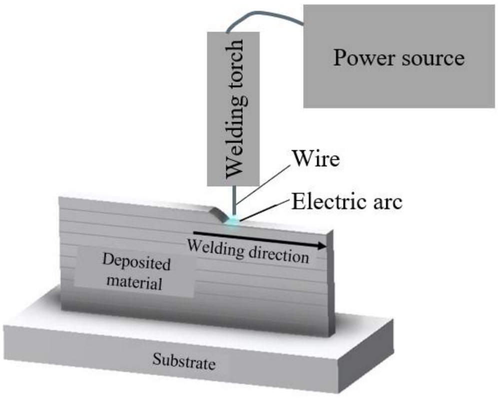

Figure 4: Schematic representation of the wire-arc directed energy deposition process, based on [20]

2. Manufacturing of parts via waDED

2.1 Methods

For evaluation of the waDED process, parts made from four different magnesium alloys were compared. The alloys were selected to represent a variety of specific properties, which are: AZ61 as reference material, AZ91CaY as a non-flammable Mg alloy and for welding of cast parts, AX13 for high yield strength, and MX1 for high ductility. The nominal chemical compositions of the alloys are given in Table 1.

Table 1: Nominal chemical composition of investigated alloys

Alloy	**Al [wt. %]**	**Zn [wt. %]**	**Mn [wt. %]**	**Ca [wt. %]**	**Y [wt. %]**	**Mg [wt. %]**
AZ61	5.8 – 7.2	0.4 – 1.5	> 0.15	–	–	Balance
AZ91CaY	8.3 – 9.7	0.3 – 1.0	0.15 – 0.50	0.20 – 0.40	0.1 – 0.3	Balance
AX13	12.0 – 15.0	0.3 – 0.6	0.15 – 0.50	0.30 – 0.50	–	Balance
MX1	–	0.7 – 0.9	0.90 – 1.10	0.50 – 0.70	–	Balance

The alloys MX1 and AZ91CaY were prepared at LKR GmbH, Ranshofen, Austria, in a resistance heated furnace in a mild steel crucible using pure elements Mg, Al, Ca, Y and Zn. Mn was added in the form of $MnCl_2$-flakes. Billets with a diameter of 65 mm and a height of 240 mm were cast, homogenized, and subsequently machined to extrusion dimension. Filler wires were produced via direct extrusion pressing to a diameter of 1.6 mm and coiled. Further details to filler wire production can be found in [4], [21]. Thin-walled structures with a wall thickness of ≈ 5 mm and a layer thickness of ≈ 2.5 mm were produced via wire-arc directed energy deposition using the gas-metal arc-welding cold metal transfer (Fronius CMT TPS) process (Figure 5). Welding speed was maintained between 10-12 mm/s and wire feed rate during steady state of 2.2 m/min. As a shielding gas during part production, the melt pool was protected using pure Ar mixed with 30 vol. % He. Samples for microstructural investigations and tensile test samples were extracted in welding direction as well as transverse direction, as shown in Figure 5 left. The manufacturing of comparable waDED parts made from AZ61 and AX13 can be found in references [3], [4].

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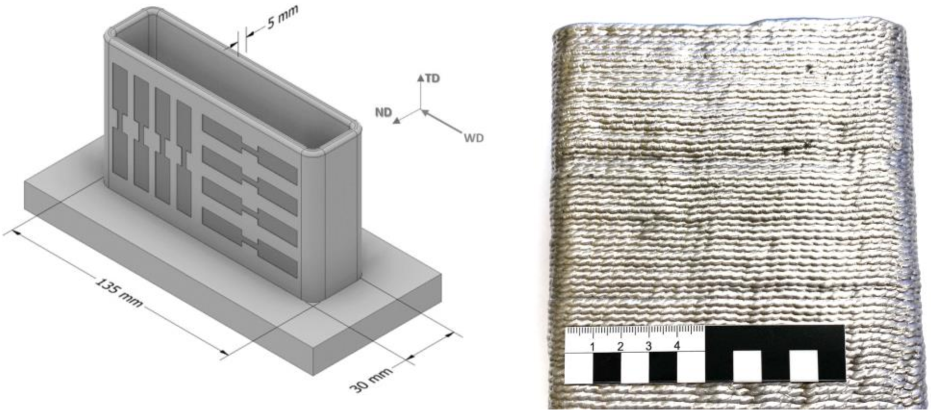

Figure 5: Schematic representation of thin-walled structure produced via waDED incl. sample extraction position (left) [21]. Front view of manufactured sample (right).

2.2 Results

The production of structural parts from magnesium alloys via waDED has been realised and deposition rates of approx. 0.4 kg/h have been achieved using wires with a diameter of 1.6 mm. A very small number of defects could be found in the manufactured parts with a total amount of porosity of < 0.03 vol.%.

Figure 6 shows exemplarily a typical microstructure of a Mg-Al-alloy manufactured via waDED in the as-fabricated state. Resulting from the high cooling speeds obtained in the process, primary intermetallic particles are evenly dispersed throughout the material. Furthermore, eutectic structures can be found on the grain boundaries, either with a lamellar or divorced (blocky) structure. For Mg-Al alloys with a significant Al-content, like AZ61, AZ91CaY and AX13, the eutectic on the grain boundaries (β-$Mg_{17}Al_{12}$) is typically divorced, as the diffusion speed of Al in Mg is low [22]. This phase can be dissolved by a solution heat treatment and subsequently precipitated by artificial aging, which allows the strength to be increased (T6 heat treatment). However, a prerequisite for the applicability of solution annealing is a low porosity of the parts used, since otherwise porosity growth can occur at the applied temperatures.

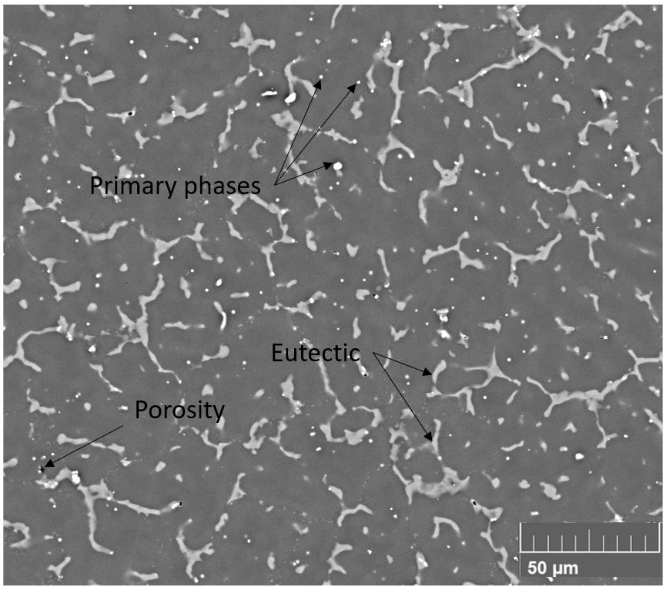

Figure 6: Typical microstructure of a Mg-Al alloy in as-fabricated state produced via waDED

The mechanical properties of the waDED parts are summarized in Table 2. As can be seen, the differences between WD and TD are small in all samples, which indicates a largely homogeneous microstructure. The YS increases with increasing Al content, starting with approx. 82 MPa for MX1 (without Al) to 100 MPa for AZ61 (with ≈ 6.5 wt.% Al) and 130 MPa for AZ91CaY (with ≈ 9 wt.% Al), while reaching its peak at 157 MPa in AX13 (≈ 13.5 wt.% Al). Furthermore, a T6 heat treatment was applied to AX13, which significantly increased both yield strength (YS) and ultimate tensile strength (UTS) without reducing elongation at break (ε_f), resulting in a YS of 190 MPa. At the same

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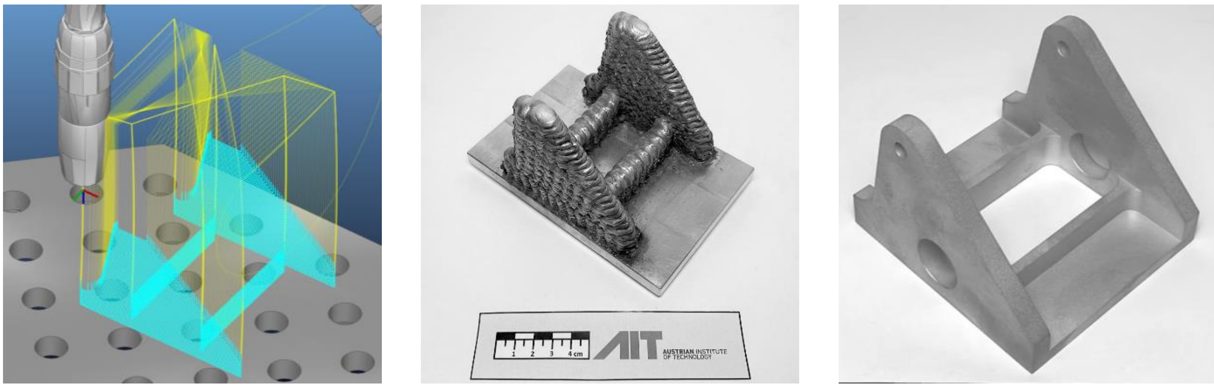
time, elongation is decreased significantly, when the Al-content is higher than 6.5 wt. %, most likely due to the formation of brittle β-$Mg_{17}Al_{12}$ on the grain boundaries. It is assumed that the elongation at break for Mg-Al alloys can be increased by application of a solution heat treatment. For AX13 in T6 state, the treatment time was too short for dissolving the divorced eutectic, therefore the elongation was only slightly improved [4].

A comparison with other processes for evaluating the waDED process was carried out for the reference alloy AZ61. For cast AZ61, a YS, UTS and elongation of 57 MPa, 159 MPa and 12.2 %, respectively [23]. Forged AZ61 achieves an UTS of 295 MPa and an elongation of 12 % [24], while for extruded AZ61, an UTS of 310 MPa and an elongation of 16 % are reported [25]. Therefore, it can be concluded that waDED can achieve mechanical properties which are superior to cast parts of the same material, while in comparison with wrought processes, the strength of waDED parts is lower while the elongation is comparable. This is not surprising since the microstructural development in waDED resembles traditional casting processes with limited melt pool volumes and high solidification rates, while effects of forming processes such as grain size reduction through recrystallization and strain hardening are not possible.

Table 2: Mechanical properties (tensile, room temperature) of waDED parts made from various Mg alloys

Alloy	State	Direction	YS [MPa]	UTS [MPa]	ε_f [%]
AZ61 (reference)	as-fabricated	WD	99.2 ± 1.7	256.4 ± 10.1	15.3 ± 3.5
		TD	104.4 ± 1.6	264.1 ± 1.8	15.4 ± 0.7
AZ91CaY	as-fabricated	WD	137.3 ± 6.5	201.2 ± 7.0	1.1 ± 0.2
		TD	124.1 ± 5.4	213.5 ± 1.7	2.6 ± 0.5
AX13	as-fabricated	Average of WD and TD	157.4 ± 2.5	209.6 ± 9.7	0.9 ± 0.2
	T6	Average of WD and TD	190.9 ± 1.4	269.2 ± 10.6	1.4 ± 0.4
MX1	as-fabricated	WD	85.5 ± 3.4	216.5 ± 1.8	23.7 ± 1.6
		TD	81.5 ± 0.6	214.0 ± 0.3	22.4 ± 2.5

In addition to the test geometry used for sampling, an application-related part was selected to demonstrate the ability of the waDED process to manufacture relevant parts within a short time. The selected geometry is modelled after a cast real-life component as used in current aircraft. The design of the additive assembly was done using the Laser Additive Manufacturing module of ModuleWorks and the offline programming of the robot motion was done using Robotmaster V6.9 (Figure 7a). The part was produced via the CMT-Puls process using a 1.2 mm wire and a layer thickness of 1.1 mm. As the contour of the selected part did not allow for a continuous welding strategy, the robot path had to be planned with four individual segments, which were applied discontinuously. After manufacturing, the body-in-white (Figure 7b) was machined to final contour (Figure 7c).
After finishing, the component surface was clean, and no pores or binding defects were detected. This highlights the possibility of future use of waDED for fast repair and replacement applications of magnesium components.



(a) (b) (c)

Figure 7: Single steps for the production of a waDED part: (a) Robot motion programming, (b) body-in-white, (c) final part after machining

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Conclusions

In this paper, additive manufacturing methods for Mg were briefly described and some results of Mg alloys processed via waDED were presented. Following conclusions can be drawn:

- Powder-based additive manufacturing processes are ideal for producing complex, filigree structures optimized for low weight, while wire-based processes allow higher production speeds at limited complexity.
- The waDED process is best suited for producing large-volume parts in low to medium quantities. Deposition rates of up to 0.4 kg/h can were realized, using a 1.6 mm wire.
- The wire-arc directed energy deposition (waDED) process has been successfully used for a variety of Mg alloys, thereby providing a wide range of properties through careful alloy selection.
- Porosity in waDED parts is small (< 0.03 vol. %) and therefore heat treatments can be successfully applied. The resulting mechanical properties are higher than those achieved by casting, but the strength is lower compared to formed (extruded or forged) parts.

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