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Laser metal deposition of magnesium alloys

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Abstract

Laser additive manufacturing (LAM) is a fast growing technology for the manufacture of metallic components. Although the activities in the area of steel, titanium and aluminium are manifold, magnesium is practically not utilized for this technology. The reason for this disregard lies in the problems of easy flammability of magnesium powder and the extensive remedial measures for powder handling. By using magnesium wire for laser metal deposition (LMD) these difficulties can be avoided. Moreover, a higher utilisation of the material can be realized. In the present study relevant influencing factors on the LMD process as well as the peculiarities for processing magnesium alloys are identified. The quality of the resulting components is assessed by non-destructive testing and the determination of microstructural and mechanical characteristics. Enabling the processing of magnesium by LAM affords new prospects for its application in the automotive, aircraft and medical industry in matters of design and properties.

Keywords: laser additive manufacturing; laser metal deposition; wire; magnesium alloy; characterisation

1. Introduction

In the recent years laser additive manufacturing (LAM) emerged as a popular manufacturing technology for metallic components, although additive manufacturing with its diverse processes is known for almost three decades. There are numerous research activities in the area of LAM of steel, titanium, aluminium and its alloys, which resulted in the industrial application of this technology. In contrast, the studies on LAM of magnesium and its alloys are very limited and up to now it is not utilized for industrial purposes. According to the “Additive Manufacturing of Magnesium Alloys Project” of the NASA, 2015, the technology maturity is still at TRL 1 (applied research).

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According to Kainer et al al., 2003, magnesium has many advantageous properties, such as its low density, high specific strength and good weldability, making it attractive for use in light-weight applications. Currently, it is utilized for special applications in the aerospace, automobile, machinery and engineering industry. Here, the magnesium alloys are usually cast or extruded, forged and machined to their final shape, as stated by Becker et al., 2003. However, thin-walled and/or more complex structures, as for example needed for medical applications, are not feasible with these conventional manufacturing techniques. For this purpose LAM is required, which enables a multitude of design freedoms. In addition, considerable material savings can be achieved with LAM.

The reason for the disregard of magnesium and its alloys for LAM in spite of the numerous advantages, lies in the problem of easy flammability of magnesium. The majority of the LAM processes used in research and industry base upon powder. Here, the powder is either deposited in a powder bed or by a powder feeding device. In both cases extensive remedial measures for the powder handling and processing have to be taken in order to avoid unintended oxidation, as for example described for selective laser melting (SLM) in the work of Ng et al., 2010, and Gieseke et al., 2013. Up to now only testing SLM facilities exist, in which solely small structures can be manufactured. Manakari et al., 2017, summarized the effects of the SLM parameters and powder properties on the processing and the resulting properties of the structures.

By the use of magnesium wire for laser metal deposition (LMD) the difficulties of magnesium powder handling and processing for powder-based LAM processes can be avoided. For this wire-based LAM process commonly used laser welding facilities can be used without or only marginal retrofitting efforts. Moreover, also conventional welding wire can be utilized for LMD. With the help of an industrial robot even complex geometries can be realized. Thus, it can be easily used for industrial purposes. In comparison to powder-based LAM processes a considerable higher utilization of material can be achieved. The higher deposition rate as well as the flexible conditions of processing enable the manufacturing of large-scale structures.

So far the wire-based LMD was solely used for the cladding of surfaces as explicated by Cao et al., 2007, Cao et al., 2008-1, and Cao et al., 2008-2. A comparable approach was taken in the study of Guo et al., 2016, in which an electric arc was utilized instead of a laser beam for the additive manufacturing of magnesium. This process is known as wire and arc additive manufacturing (WAAM). However, the working distance for an electric arc is considerable lower as for a laser beam, which finally can lead to restrictions in accessibility. Furthermore, thicknesses of walls are assumed to be larger.

In the present study, the relevant influencing factors on the LMD process as well as the peculiarities for processing of magnesium alloys are identified, using the example of AZ31. The quality of the resulting structures is assessed by non-destructive testing and the determination of the microstructural and local mechanical characteristics.

2. Materials and experimental procedures

2.1. Materials

For the LMD experiments a commercially available AZ31X wire (Drahtwerk ELISENTHAL) with a diameter of 1.2 mm was used. The material was deposited on a substrate of the same material, AZ31-HP, rolled to a thickness of 5.0 mm. AZ31 is a wrought magnesium alloy with aluminium and zinc as primary alloying elements. The exact chemical composition of both wire and sheet material, determined experimentally by energy dispersive X-ray analysis, is summarized in Table 1.

Table 1. Chemical composition (in wt.%) of the wire and substrate material.

material		Al	Zn	Mn	Si	Fe	Mg
AZ31X	wire	2.67	1.12	0.14	0.07	-	Bal.
AZ31-HP	substrate	2.64	0.59	0.11	-	0.03	Bal.

Prior to the LMD process the substrate was cleaned with alcohol, in order to avoid unintended contamination.

2.2. Laser metal deposition

The LMD was performed using a 3-axial CNC machining centre connected to an ytterbium fibre laser with a maximum laser power of 8.0 kW. The laser fibre had a diameter of 300 µm. The optical device had a focal length of 300 mm and a collimator length of 120 mm. This resulted in a focus spot diameter of 746 µm (determined experimentally with the laser beam diagnostic system Primes Focus Monitor). By defocusing in positive direction (above surface) an increase of the spot diameter could be realized. The used laser system had a top-hat intensity distribution providing a uniform distribution of energy. The wire was supplied in the dragging configuration enabling a stable wire feeding. In order to avoid unintended oxidization of the magnesium melt, argon was used as shielding gas, which was also supplied in the dragging configuration with a flow rate of 13 l/min. The used laser welding configuration is depicted in Fig. 1.

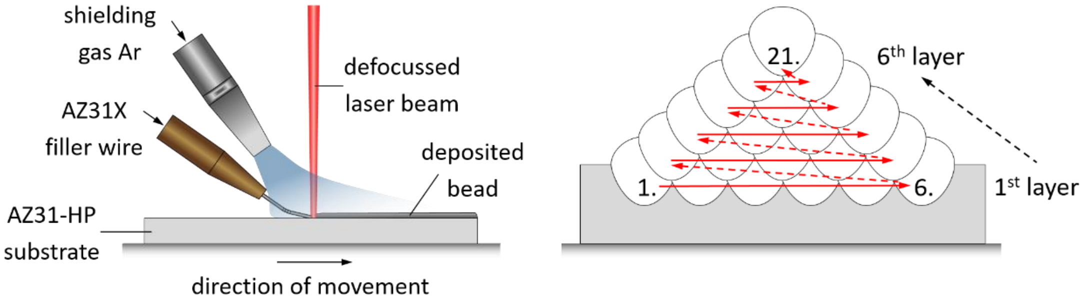

Fig. 1. Configuration for laser metal deposition with wire (left) and strategy for the manufacture of a pyramid structure (right).

For the feasibility study a simple pyramid structure was chosen, built up of 21 individual deposition beads and 6 deposition layers. The used strategy for building the pyramid structure is also shown in Fig. 1. The corresponding LMD process parameters, optimized in a preliminary study, are given in Table 2.

Table 2. Process parameters for the laser metal deposition of the pyramid structure.

laser power [kW]	deposition velocity [m/min]	wire feed rate [m/min]	spacing between beads [mm]	height offset [mm]	pre-heating temperature [°C]
2.0	2.3	4.0	2.2	0.6	w/o
2.0	2.3	4.0	2.2	0.6	150
2.0	2.3	4.0	2.5	0.7	300

The pre-heating to elevated temperature (150°C and 300°C) was performed using a heating plate of the same size as the substrate, which was placed underneath the substrate. The temperature was monitored with the help of thermocouples.

2.3. Assessment of the process quality and the resulting structures

The LMD of the magnesium wire was monitored with the help of a high speed camera, in order to assess the process stability.

Inner defects, such as porosity and cracks, were determined with the help of radiographic testing according to EN ISO 17636-1. The outer appearance, in terms of surface defects and evenness, was assessed by visual inspection.

Besides the non-destructive testing, the microstructural properties were investigated with optical microscopy. The used etching agent based on picric acid. The local chemical composition was determined by energy dispersive X-ray (EDX) analysis with a scanning electron microscope equipped an EDX Si(Li) detector. The local mechanical properties were determined with the help of Vickers microhardness indentation testing according to DIN EN ISO 6507-1. For this purpose a semi-automatic hardness testing device with a test load of 0.981 N (HV0.1) and an indentation time of 15 s was used. The indentations were set in the centre of the pyramid structure.

3. Results and discussion

3.1. Peculiarities of laser metal deposition process

After the deposition of each individual bead a film of bright-coloured deposit was observed on the surface of the bead and in its vicinity. In case of multi-layer deposition an accumulation of this deposit on the structure surface was observed. By subsequent cleaning with a wire brush, the deposit film could be easily and residue-free removed. The extent of the deposition film in case of LMD without intermediate cleaning is shown in Fig. 2. The observed colour variations can be explained by different exposure temperatures resulting in different oxidations conditions of the deposit.

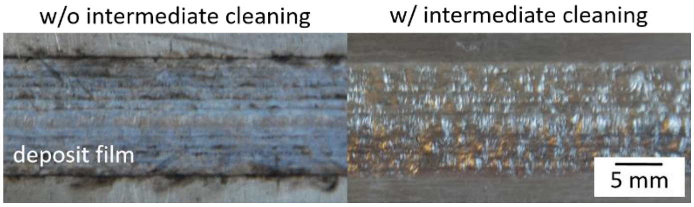

Fig. 2. Surface appearance (top view) of a laser metal deposited pyramid structure at room temperature without and with intermediate cleaning after each deposition of a bead.

The origin of this deposit is assumed to be the smoulder formed during the LMD process by the vaporisation of volatile elements, such as magnesium and zinc. This was verified with the help of the high-speed camera recording (Fig. 3). Although the smoulder was blown away by the shielding gas in the area of the melt, the vaporized metal condensed on the surface of the behind solidified melt.

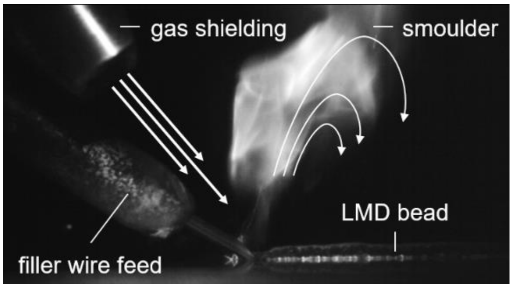

Fig. 3. High-speed recording screenshot (side view) of the laser metal deposition of an individual bead and the smoulder formation.

The observation of the LMD process with a high-speed camera also showed that the right choice of LMD parameters resulted in a stable deposition of magnesium wire. Besides smoulder, no considerable spatter formation was observed. Furthermore, very even and uniform deposited beads were obtained.

Due to the higher heat input during LMD, required for the melting of the wire and the subjacent substrate, the residual stresses and thus the distortion is assumed to be considerable larger as in comparison to powder-based SLM. Therefore, an appropriate clamping of the substrate was of great importance. By pre-heating of the substrate to 150°C and 300°C it was possible to decrease the degree of distortion to some extent. The introduction of intermediate cooling intervals after the deposition of each individual bead (for example for the intermediate removal of the deposit) led also to a reduction of the final distortion of the substrate. However, this led to an unreasonable increase of the LMD processing time.

3.2. Non-destructive quality assessment of the laser metal deposited structures

From the radiographs of the obtained LMD structures it could be deduced that no macroscopic defects, such as pores or cracks, were present, as it can be seen in Fig. 4. Only a slight surface unevenness is visible.

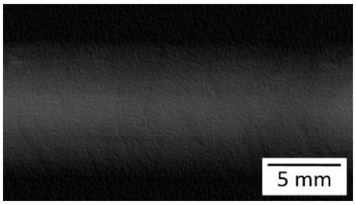

Fig. 4. Radiograph (top view) of a pyramid structure without macroscopic defects laser metal deposited at room temperature.

Another advantage of pre-heating the substrate to elevated temperatures for LMD is the improvement of the surface roughness. For higher initial substrate temperatures considerable smoother surfaces were obtained (Fig. 5). A comparable effect was observed by Savalani et al., 2016, for SLM structures made of pure magnesium.

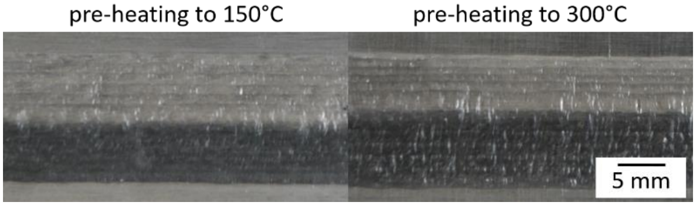

Fig. 5. Surface appearance of the pre-heated pyramid structures.

A preliminary study of the authors showed that comparable results, in matters of surface quality, were obtained for pyramid structures built up of 14 layers.

3.3. Microstructural characteristics and local chemical composition

As described in detail in the work of Cao et al., 2008-2, there is a strong influence of the LMD parameters, mainly laser power, deposition velocity and wire feed rate, on the size and shape of the individual beads. For the LMD of multi-layer structures, the spacing between the beads as well as the height offset play also an important role for obtaining smooth structure surfaces, as discussed by Cao et al., 2008-1. In case of pyramid structures these findings could also be applied. As it can be seen in Fig. 6, the pre-heating has also an influence on the size of the individual bead. For increasing temperatures, the bead width (W) and height (H) as well as the penetration depth increases. However, the aspect ratio of the beads always kept constant at approximately 1.1. Due to the change of the bead dimensions, an adjustment of the LMD parameters, in terms of bead spacing and height offset was necessary (Table 2).

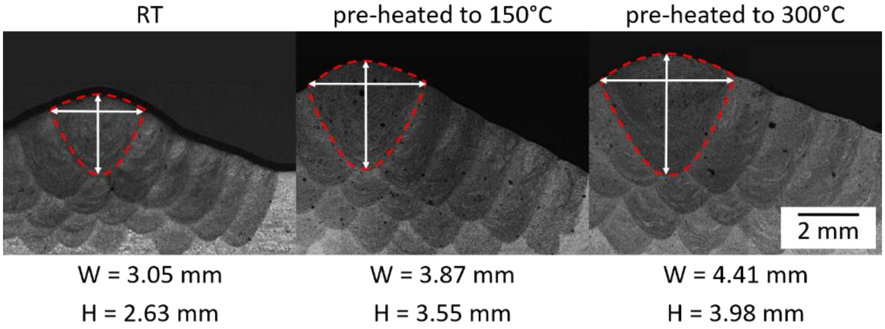

Fig. 6. Dimensions of the laser metal deposited beads and the resulting pyramid structures for different pre-heating temperatures.

As described earlier, a distinct smoulder formation due to the vaporisation of volatile elements was observed during the LMD processing of the magnesium wire. Although zinc has with 907°C the lowest vaporisation temperature of the three main constituents of the magnesium alloy AZ31X, a noticeable loss of approximately 0.65 wt.% in comparison to the initial composition of the filler wire was only observed for magnesium (with a vaporisation temperature of 1110°C and a high vapour pressure of 360Pa at its melting temperature) at the top of the last layer. In contrast, the zinc concentration was almost constant due to its moderate vaporisation temperature and vapour pressure.

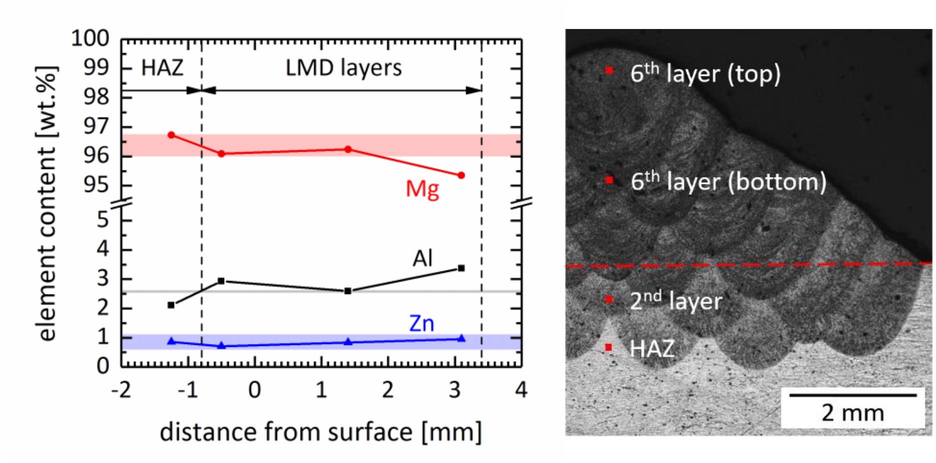

Fig. 7. Change of the chemical composition in the laser metal deposited structure with 6 layers. The shaded areas indicate the initial composition range of the substrate and the wire according to Table 1 (left). Positions of the EDX measurements in the structure (right).

The apparent increase of the aluminium content was not caused by the additive of it but can be explained by the fact that the relative proportion of it is increased. Aluminium has with 2470°C the highest vaporisation temperature and with approximately 10^{-6}Pa the lowest vapour pressure at its melting temperature. For this reason no loss of aluminium was observed.

Although, a distinct deposit film of oxidised elements was observed on the surface of the LMD structure no negative effect on the microstructure was detected. In contrast, slightly lower defect levels, in terms of microporosity, were detected in case of no intermediate cleaning, as depicted in Fig. 8. However, for the more filigree SLM structures a negative effect of the deposit on the microstructure was observed by Zhang et al., 2012. Moreover, the LMD structure without intermediate cleaning results in a lower structure height. This can be explained by the fact that due to intermediate cleaning a cooling of the structure results.

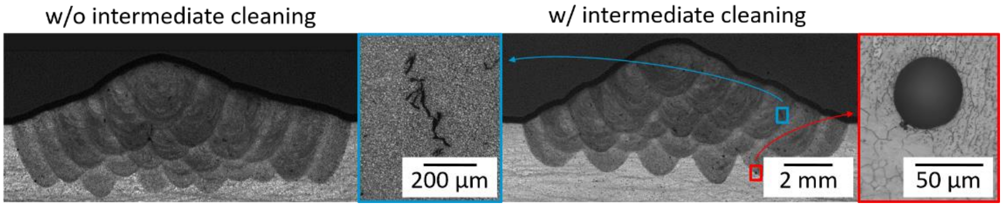

Fig. 8. Macrographs of pyramid structures laser metal deposited without (left) and with (right) intermediate removal of the deposit.

3.4. Local mechanical properties

The results of the microhardness measurements are shown in Fig. 9. In comparison to the base material (BM) of the substrate with a mean hardness of 56.6±2.3 HV0.1 an increase of hardness was observed for the heat affected zone (HAZ) of the substrate with 61.4±2.9 HV0.1 and the LMD layers with 63.0±2.9 HV0.1. This means that the average hardness increase only 6.4 HV0.1.

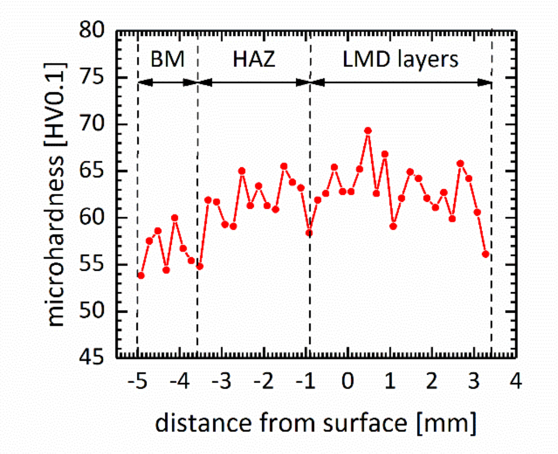

Fig. 9. Microhardness profile of a pyramid structure laser metal deposited at room temperature.

From the hardness profile it can be deduced that the local mechanical properties, in terms of Vickers microhardness, are almost constant in thickness direction. Due to this fact, the proposed wire-based LMD process can also be applied for repair of already existing magnesium structures.

4. Conclusions

Based on the results obtained in this study the following conclusions can be drawn:

- The wire-based LMD process simplified the processability of magnesium for additive manufacturing purposes, since no special measures for the handling of magnesium wire are required and commonly used laser welding facilities are capable for this process.
- By LMD with wire magnesium structures with a very low defect level or even without any defects can be obtained. Moreover, the resulting structures possess very smooth surfaces.
- The microstructure of the LMD structures is comparable to laser weld seams. The loss of volatile elements is comparatively small.
- The local mechanical properties of the LMD structure, in terms of Vickers microhardness, showed only an insignificant increase in comparison the substrate base material.
- The wire-based LMD process affords new prospects for the application of magnesium in different industrial sectors in matters of design and properties.

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