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Process development for wire-based laser metal deposition of 5087 aluminium alloy by using fibre laser

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ABSTRACT

In recent decades, laser metal deposition, as a part of additive manufacturing, developed into a promising methodology in industrial fields. In recent years, there has been an increased interest in the processability of lightweight high-strength structural materials, such as aluminium alloys. However, in terms of wire-based laser metal deposition, there is still a lack of knowledge with regard to the processability of aluminium alloys. In this research, the process development for wire-based laser metal deposition of a 5087 aluminium alloy (AlMg4.5 MnZr) has been conducted. It is observed that pre-heating is beneficial in terms of porosity and distortion reduction. Within optimized parameter ranges, it is possible to control the geometric shape, dilution, and aspect ratios of the deposited layers in a systematic way. Accordingly, defect-free layers with tailored geometrical features can be processed and adapted to specific process requirements.

1. Introduction

From its development in the late 1980s, additive manufacturing (AM) has become a profitable method to generate components and structures for industrial use today. The concept of this technique consists of melting a material, usually provided as powder or wire, and adding it layer-by-layer to build components, instead of subtractive manufacturing, such as cutting or milling [1–4]. Therefore, AM enables a high degree of freedom from the construction point of view, and includes great advantages in terms of the degree of utilization, including an inherent simplicity in building three-dimensional shaped parts [5]. In comparison to conventional machining methods, AM leads to a significant reduction of material wastage from up to 90 percent for machining down to less than 10 percent for AM [6,7]. In addition, saving the tool change time per part, the costs and cycle time can be minimized [8]. From an economic point of view, the fabrication of wire material in contrast to powder is comparably cheap. Therefore, processing wire, instead of powder raw material, is very interesting for industrial applications [9].

In the field of AM, many different approaches have been developed over recent decades. With regard to the production of metallic parts, these approaches are divided into powder-and wire-based techniques [8,10,11]. Powder-based approaches have already achieved significant application in several industrial fields [8,12]. These approaches are subdivided in powder bed and powder injection techniques [11,13]. In case of powder bed systems, such as selective laser melting (SLM), a certain amount of pulverized metallic material has to be supplied in a processing chamber that is flooded by shielding gas. This powder material is locally irradiated by a laser beam, which follows a predefined path according to a computational design. After the solidification of the molten material, a subsequent layer of powder material is automatically placed on top of the manufactured structure. This method is repeated until the desired shape of the component is manufactured. In contrast, in powder injection approaches, the pulverized material is supplied through a nozzle. After the material leaves the nozzle, it is melted by a laser beam and added to the workpiece in order to produce the desired shape of the final component. An inert gas, such as argon or helium, is used to blow the pulverized material on the workpiece, which simultaneously protects the melt pool from reacting with atmospheric gases.

In wire-based approaches, the wire is fed through a nozzle on to the workpiece to add certain layers of material on top of or next to each other. Similar to powder injection approaches, the material is shielded by an inert gas during the molten state. However, the surface area of the injected wire by using wire-based AM is much lower than the accumulated surface area of the powder particles in powder-based approaches, which reduces the hazard of possible reactions with atmospheric gases. Therefore, it is not necessary to work in a closed chamber

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of an inert gas, which drastically increases the degree of freedom for the applications of the wire-based approach. In addition, AM, by using wire-feeding systems, offers a higher usage efficiency of a material [14], improved surface quality of the deposited structures [3,9], and enables higher deposition rates [3] in comparison to powder-feeding systems.

For AM, the minimization of post-processing is one of the most important aspects [15]. In this regard, milling to straighten surface roughness is primarily conducted. This results in a certain amount of waste material and additional manufacturing costs. In order to reduce the amount of waste material and production costs, near net shaped components are targeted. For this purpose, process windows have to be precisely configured in such a way that high efficiency can be achieved.

In this contribution, a laser metal deposition (LMD) technique, using filler wire as raw material and laser as energy input, is investigated. This approach offers high deposition rates in a well-controllable process [15,16]. Local shielding in the melting zone is applied. Owing to high adaptability in industrial fields, a process development addressing the identification of important parameters in the LMD of the aluminium alloy 5087, with particular attention paid to the resulting macro-morphology, is investigated. Therefore, a parametric study including the examination of the possible defects and surface quality of the specimens is conducted.

2. Experimental study

2.1. Materials

In this study, the aluminium alloy AlMg4.5 MnZr (EN AW-5087) as wire-material and AlMg3 (EN AW-5754) as substrate-material were investigated. The 5xxx aluminium series is characterized to be the stiffest with respect to non-heat treatable aluminium alloys [17]. The wire was provided with a diameter of 1.0 mm by using a speed-controlled automatic feeding device. The substrate material was provided in 200 mm × 150 mm rolled sheets, with a thickness of 6 mm. The deposition direction was adjusted perpendicular to the rolling direction of the substrate material. Owing to the high reflectivity of aluminium and, furthermore, in order to clean the surface of the substrate material, the substrate was firstly sandblasted and cleaned with acetone before LMD. A pressure of 8 bar and a particle size between 90 and 150 μm of the blasting material was used to achieve a surface roughness of $R_a = 0.20$ μm of the substrate material.

2.2. Experimental setup

An 8-kW continuous wave ytterbium fibre laser YLS-8000-S2-Y12 (IPG Photonics Corporation) integrated with the optical head YW52 Precitec, in a CNC-supported XYZ-machining centre (IXION Corporation), was employed in this study. The optical head was integrated along the Z-axis of the system, which was also equipped with a wire-feeding system along with a local shielding gas supply, as schematically illustrated in Fig. 1.

The wire was fed through a nozzle at a fixed angle of β = 35°, relative to the surface of the substrate. The nozzle for a local shielding gas supply was installed above the wire nozzle with an angle of γ = 55°, a vertical distance of 25 mm, and horizontal spacing of 5 mm relative to the tip of the wire-feeding nozzle. The shielding gas flow rate was adjusted to 10 l/min, thus providing enough gas to protect the molten material from oxidation with atmospheric gases but not influencing the solidification process. Owing to the high viscosity of aluminium in its liquid state and in combination with a very high cooling rate within the LMD process, the shape of the deposited structure could be distorted by using a very strong gas flow. As an alternative, the deposition could be conducted in a complete shielding gas atmosphere, such as an argon-filled chamber. However, this approach is less adaptable within industrial applications due to geometric restrictions.

The circular shaped laser beam irradiates the wire perpendicular to

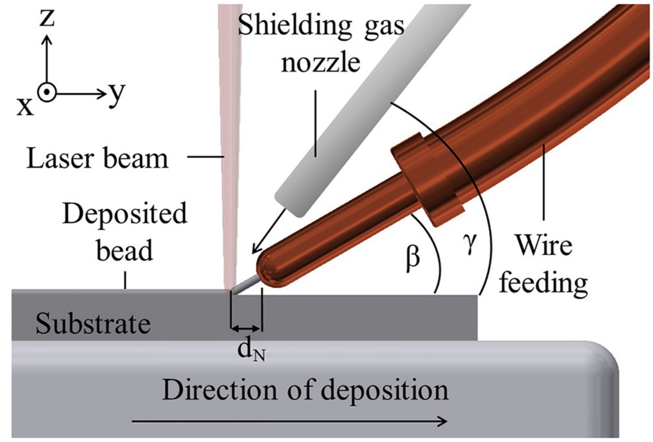

Fig. 1. Schematic visualization of the laser metal deposition (LMD) process. The fixed process parameters where illustrated; these include the flow rate of shielding gas Q_{Ar}, the shielding gas nozzle angle γ, the wire feeding nozzle angle β, the focal spot to wire-feeding nozzle tip distance d_N, and the direction of deposition.

the substrate. Owing to the fact that the wire is supplied on a coil, it has an inherent cast that might affect the feeding accuracy by an oscillating movement of the wire tip after leaving the nozzle. The laser spot diameter was enhanced to 1.6 mm by positive defocusing to + 23 mm. By this, the occurring oscillations of the wire were compensated and the substrate could also be partly molten during the deposition, thereby leading to an additional stabilization of the process, resulting in a minimization of bonding defects between the substrate and the deposited material. The distance between the focal spot and the edge of the wire-feeding nozzle was adjusted to be as minimal as possible in order to reduce the oscillating movements of the wire and to improve process accuracy. A distance of $d_N = 4$ mm could be identified as the minimum distance to ensure that the tip of the wire nozzle was not molten during the process but also large enough to avoid remaining not molten material on the nozzle after switching off the laser. Otherwise, this remaining material might be melted again at the deposition of the next bead and could fall on the substrate, leading to defects. The same effect might occur during the process-related development of smoulder. Within the process, the table of the CNC-system was moved in relation to the z-axis in the x or y direction at a defined deposition velocity v_t. Simultaneously, the wire was fed through the nozzle at a velocity v_w. Using the presented process, it was possible to deposit lines of AlMg4.5 MnZr on the AlMg3 substrate and to regulate the deposition rate by adjusting the ratio between v_w and v_t, named $k = v_w/v_t$ as used, for example, in [18].

The main characteristics of the used laser source and the features of the focused beam are shown in Fig. 2 and summarized in Table 1. In Fig. 2(a) and (b), the caustic of the focused beam and its symmetry for the used equipment has been visualized. Furthermore, the beam intensity for the focal position (c) as well as for the Rayleigh length (d) is plotted in Fig. 2. It can be seen that a top hat distribution is achieved by using the focal position, whereas a Gaussian distribution shape is formed in the Rayleigh length. Furthermore, a possible elliptical shaping of the laser spot area due to angular relations with respect to the substrate surface was balanced by the adjustment of the equipment and a linear deposition path in perpendicular orientation to the substrate surface. For complex structures requiring curved or circularly paths, the angular relations between the optical head and the surface of the structure have to be taken into account. In this study, only straight-lined beads have been considered.

2.3. Experimental procedure

Table 2 provides an overview of the varied process parameters