12th CIRP Conference on
Photonic Technologies [LANE 2022]

Industrial Paper

Laser Metal Deposition as a means for repairing, hybrid, and Additive Manufacturing

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Abstract

Laser Metal Deposition (LMD) adoption as industrial fabrication method of entire parts is still precluded by several limitations involving: design and programming, process productivity and efficiency, and final quality of the part. Conversely, LMD in repairing and hybrid manufacturing is becoming a consolidated alternative to traditional processes.

This article offers an overview of the maturity of powder and wire LMD processes at Politecnico di Milano with a focus on capabilities and limits offered by LMD technology for production of entire parts. Based on experience matured in powder and wire LMD processes, LMD applications are presented and discussed together with the issues requiring attention from the point of view of part design and process system capabilities. The study provides an analysis of the challenges in LMD, with a holistic view encompassing three fundamental steps of the LMD process chain: 1) off-line tool path programming, 2) optimization of process conditions, productivity and efficiency, 3) defect-free production of high value and large parts through in-line monitoring and control.

Keywords:"wire and powder laser metal deposition; off-line tool path programming; productivity and efficiency, process monitoring ".

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1. Introduction

Since its debut, LMD has immediately shown its strength points compared to PBF. These include: i) large parts manufacturing, not limited by the size of the powder bed, although large volumes become an issue if the atmosphere needs to be controlled; ii) tailored material composition, enabling development of functionally graded material and combinatorial material as well as site-specific composition control; iii) complex 3D tool trajectory, not necessarily 2.5D and not necessarily requiring supports that are difficult to print with LMD; iv) integration with subtractive processes as well as hybrid manufacturing where the substrate can be the surface of a component partially produced by other manufacturing methods.

Conversely, the weaknesses of LMD technology, when compared with the PBF processes, are also very clear today: i) coarser feature resolution and limited capability in the realization of complex near net-shape features, such as cavities and internal channels, lattices and porous structures, bio-inspired and topology optimized parts, ii) low surface quality and coarse roughness with pronounced stair-stepping effect, iii) columnar/equiaxed transformation in the final microstructure with an increase in the grain size with the number of layer increasing and aging of the already deposited layers due to numerous reheating cycles.

Applications of powder or wire LMD process may be grouped in 3 basic classes: 1) manufacturing of entire components, 2) partial built-up of features on existing base bodies, 3) repair of damaged, worn or incorrectly produced parts. Repairing, remanufacturing, and restoring of high value existing components has broad application prospects. On the other hand, LMD manufacturing of entire parts is less common and is limited to products with a simple geometry, often with axial symmetry and large dimensions, with reduced resolution or where post processing machining operations can be performed. Fig.1 shows the examples of two products entirely printed via powder LMD at Politecnico di Milano: the exhaust system of the MV Agusta Brutale motorbike (Fig.1a) and a multi-material burner (Fig.1b).

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In order to consider LMD as a production method, particularly for the production of whole parts, three main challenges need to be addressed:

1. off-line tool path programming and CAM post-processor (especially for robotic system);
2. optimization of process parameter conditions, productivity, and efficiency;
3. in-line sensing, monitoring and control.

Therefore, they are central topics in the LMD research and investigation at Politecnico di Milano.

2. Key challenges in powder and wire LMD

The LMD system at the Department of Mechanical Engineering of Politecnico di Milano is a flexible and open architecture cell (ADDITUBE, BLM Group, see Fig.1c). The deposition head is mounted on the end-effector of the 6-axis anthropomorphic robot (ABB IRB 4600-45), while the workpiece is fixed on the 2 axis rotating and tilting table (ABB IRBP A 250).

The end-effector of the ABB robot has a flexible interface that allows to easily interchange a powder LMD head (Kuka Industries MWO-I-Powder) with a coaxial nozzle (Fraunhofer ILT COAX 40 F), see Fig.1c, or a wire LMD head (CoaxPrinter, Precitec), see Fig.1d. A powder feed system (GTV TWIN PF 2/2-MF) or a wire feed system (Carpano Equipment Viper VPR-03) are used when performing powder or wire LMD respectively. The Additube cell includes an IPG YLS-3000 active fiber laser source operating at 1070 nm and 3000 W of maximum power. A 400 µm process fiber delivers the laser beam to the powder or wire deposition head.

As better explained elsewhere (Motta et al. 2018), the wire head is an annular spot with 1.0 mm diameter at the focal plane and works with wire diameter in the range 0.8-1.6 mm.

The powder head has a 129 mm focal length of the collimation and a 200 mm focal length of focusing lenses respectively. Adjusting the collimation, the laser spot diameter ranges in the interval 0.7-3.5 mm on the working plane. A monitoring device is coaxially integrated in the optical path of the power deposition head. Three coaxial sensors detect the in-line emission from the melt pool. They include: i) a NIR camera with a 0.8-1 µm band-pass filter for melt pool form detection (xiQ USB3 Vision Camera MQ013xG, Ximea); ii) a two-color pyrometer, with two wavelength bands, namely 1.6-1.75 µm and 1.7-2.0 µm, for temperature sensing, in close loop with the laser power as controlled function (LASCON® LPC04, Dr.Mergenthaler); iii) a patented coaxial triangulator for detection of the stand-off distance and correlated track height (Donadello et al. 2018).

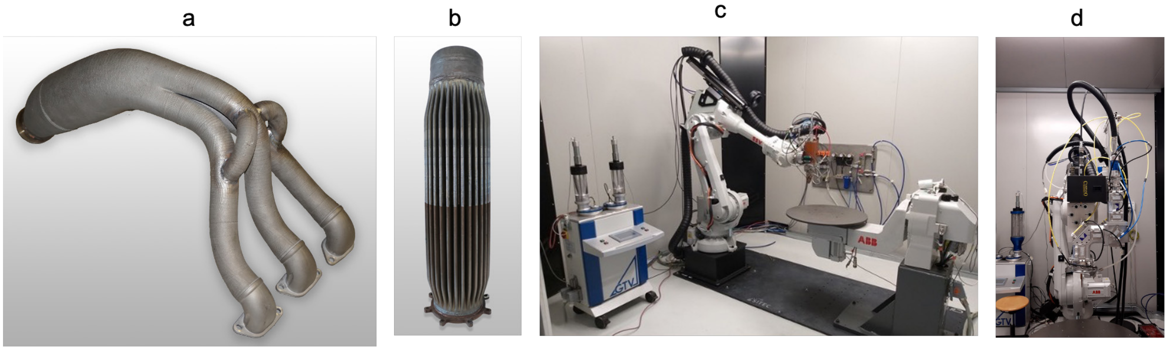

Fig. 1. (a) Motorcycle exhaust manufactured via powder LMD in a single piece in SS 316L (courtesy of Lafranconi, https://www.youtube.com/watch?v=SN2oDExzX2o), (b) industrial burner manufactured via powder LMD in bi-material, bottom SS 316L and top Inconel 718 (courtesy of Tenova, https://www.youtube.com/watch?v=5IS14vGx5zs&t), (c) ADDITUBE Robotic LMD system configured with powder deposition head, (d) detail of ADDITUBE configurated with the wire deposition.

2.1. Off-line tool path programming and postprocessing

The nature of the LMD process allows to deposit material in a multi-axis configuration. This offers more freedom than other 3D printing processes, which are commonly constrained to a growth along a constant z-direction. The multi-axis capability makes LMD a perfect candidate for the realization of complex parts with overhanging features but must be properly supported by the handling systems.

Off-line programming of the tool path for complex 3D parts is still in the early stage, where cartesian CAM tools directly derive their solution from the long tradition matured in the 5 axis milling machines applications. Conversely, 6 +2 axis robot manipulators base off-line tool path programming on proprietary solutions that start from a simple slicing tool, then develop path programming and end with simulation and collision verification in a resident ambient.

CAM Post-processors and tool path generators are, however, often limited to proprietary robot controls and not specifically developed for LMD process (Bhatt et al. 2020). The immaturity in the off-line programming and post-processing of the robotic tool slows down the adoption of the LMD as manufacturing method.

Fig. 2. (a) Categorised forms in the analysis of robotic powder LMD, (b) LMD printed exemplars of some categorised forms.

In Politecnico di Milano a critical review of the main off-line tool path programming for robotic LMD systems has been carried out. The review interested both general purpose and specific software solutions. They have been tested by means of a set of demonstrative geometries possessing features that are crucial for deposition processes from a geometrical and kinematical point of view (see the categorized forms in Fig.2a). Some of the mentioned CAM-programmed parts have also been realized with the ADDITUBE robotic LMD system in SS AISI316L (Fig.2b). Then, the built components were characterized with a 3D vision-based metrological approach to assess the effectiveness of the employed CAM solution. The main issue encountered was the lack of proper integration between the CAM environment and the robotic programming one. Indeed, robotic-driven LMD raises some novel and ever seen challenges to robots. This is due to the peculiarities and needs of LMD processes, which are radically different from traditional robotic applications. The development of a robotic LMD software should account for these concerns and provide dedicated tools along the whole process planning workflow.

2.2. Optimization of Process Parameter Conditions, Productivity and Efficiency

Powder LMD has been investigated heavily in the last several years with the aim of determining the feasibility window as well as the process parameter conditions for the most common metallic alloys. At Politecnico di Milano we have explored the process conditions and feasibility window for Ti6Al4Va, stainless steel AISI 316L, Inconel 625 and 718, CoCrMo alloys. Fundamentally, two different set of process parameters are found: High Deposition Rate (HDR) LMD and Common Deposition Rate (CDR) LMD. These two regimes are distinguished by not only different deposition rate but also different feature resolution and surface roughness (see Candel-Ruiz 2015, Li 2022, Zhong 2015). Typical HDR LMD is more productive (deposition rate around 2kg/h) and more powder efficient (powder yield more than 90%), depending on deposit material (stainless steel or Ni or Co based alloys), spot size, laser power and traverse speed but less detailed and fine-resolved. On the other hand, CDR LMD has lower productivity, discards more than 40% of the powder, but is capable of fines features and low roughness. In the laser cladding process, the two categories are also present, where the extreme high-speed laser material deposition (EHLA) allows deposition at high process speeds in the range of several hundred meters per minute (Schaible 2015). On the other side, wire LMD is known to be very productive, 100% wire efficient, although it is less investigated.

2.3. In-line sensing, monitoring and control

One of the most challenging goals in powder and wire LMD is the in situ real-time monitoring for high-value applications where component failures are not admitted. This is achieved by directly measuring the deposition characteristics (temperature, melt pool size, deposit height, etc.) during the process and correlating them to the input process parameters (Wang, H., Zhang H. 2020). Different monitoring methods have been adopted in LMD, either through thermal measurements or through measurements based on visible light. Sensing systems mainly focus on in situ monitoring of the melt pool in terms of temperature and size, sensors to monitor the material flow rate and in situ monitoring of the deposit geometry (height and width). However, these are often studied separately, providing only partial information about the process under selected operating conditions. In Politecnico we are experimenting multi-channel sensing with a sensorised head allowing three signals acquisition: melt pool IR intensity by means of a two colour pyrometer, melt pool area MP_{area} through a CMOS camera and stand-off distance SOD measurement through a triangulation system. In Fig.3 a nominal cone geometry was realised in two ways: in open-loop without maintaining a constant temperature of the molten pool (see Fig.3a), or in close-loop with temperature control throughout laser power modulation (see Fig.3b), while the 3 signals were acquired.

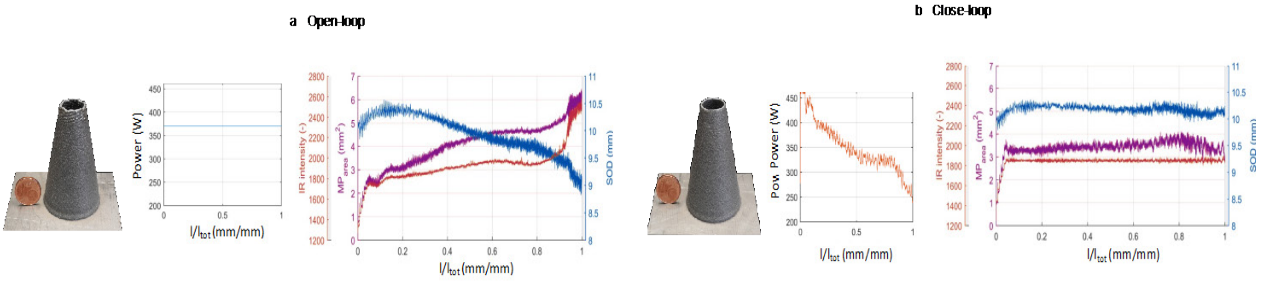

Fig. 3. (a) Printed cone, laser power signal and comparison between 3 coaxial signals from the molten pool, i.e. IR intensity, MP_{area} and stand-off distance SOD in open loop LMD; (b) Printed cone, laser power signal and comparison between 3 coaxial signals from the molten pool, .e. IR intensity, area MP_{area} and stand-off distance SOD in open loop LMD

In the case of deposition without the closed-loop control an initial transient is present in the monitored signals, which tend to stabilize once the process proceeds toward a stable regime. However, considering that the cone geometry introduces strongly variable heat accumulation and cooling rates, a self-regulating mechanism cannot be fully established. In particular, at the end of the deposition it can be observed a strong departure of melt pool area and stand-off distance from their stable values. Such departure can be mainly related to the temperature increment observed with the pyrometer. Conversely, in the case of deposition with closed-loop control, the laser power is controlled in order to stabilize the pyrometer signal. Therefore, temperature variations are compensated during the different geometrical conditions. As it can be observed from Fig.3b the temperature signal remains almost constant during the whole deposition, except the initial transient. The stability of the geometrical signals (SOD and melt pool area) is also strongly improved.

These observations show that a closed-loop control based on thermal emission can be effective for a partial process stabilization and geometrical control.

3. Conclusions

Although currently less common than PBF for metal AM applications, LMD offers much more freedom in material domain, allowing the fabrication of multi-material structures and the design of alloys, in particular for large structures due to the free form of the construction environment with 6 and more axis robotic systems. Finally, wire LMD systems are also becoming popular, because more efficient, safe and productive.

However, adopting LMD as industrial fabrication method requires overcoming barriers in tool path programming, in optimizing process parameters in view of efficiency and productivity and controlling the main process inputs in close-loop to ensure defect-free printed parts. This paper reviews recent advances in wire and powder LMD along with associated processing conditions, monitoring methods and printing systems.

Acknowledgements

BLM Group, Nuovo Pignone (Baker Hughes) Precitec and Team 3D-Siemens are gratefully acknowledged for hardware and technical support provided. Lafranconi, Tenova and ABB industrial case studies are greatly appreciated.

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