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Feasibility of LMD-w for the manufacturing and combined manufacturing of industrial applications

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Abstract

Laser Metal Wire Deposition (LMD-w) is currently considered one of the most promising Additive Manufacturing (AM) technologies for the fabrication of freeform metal components in various application fields. This includes sectors such as construction, power generation and aerospace industries, where the fabrication of complex parts is essential. Wire feedstock offers a clean, safe, and cost-effective alternative to powder feedstock, while still maintaining the necessary productivity to meet industry demand. However, the manufacturing of complex components raises concerns regarding the achievable mechanical properties and their uniformity across the entire workpiece. This becomes particularly important in cases where LMD-w is used for repairing existing components or combined with traditional technologies for the manufacturing of workpieces. The objective of this study is to address these concerns by presenting a representative component fabricated by LMD-w and investigating its mechanical properties under different process conditions. The findings of this investigation aim to provide valuable insights for the manufacturing of actual industrial components.

Keywords: LMD wire; mechanical properties; combined manufacturing; industrial components

1. Introduction

Laser Metal Wire Deposition (LMD-w) is currently recognized as one of the most promising Additive Manufacturing (AM) technologies for the fabrication of freeform metal components. This is attributed to its notable advantages, such as high deposition rates, material efficiency, low safety risks, reduced feedstock cost and convenient material handling. The potential application fields for the technology span across various industries, including construction, power generation and aerospace.

Industrial cases often involve repairing application or application where the LMD-w technology is employed combined with traditional technologies. However, there is a notable scarcity of studies in literature focusing on LMD-w fabrication of geometries over existing components. This specific manufacturing approach is referred to as “Comanufacturing” (combined manufacturing) in the present work. The existing studies refer to hybrid manufacturing in terms of combining additive manufacturing and subtractive manufacturing for repair applications and in terms of combining more AM processes to obtain the final part as exemplified by Popov at al., 2020 and Rittinghaus et al., 2020. Notable examples of real-world cases where comanufacturing could find application are evident in the research conducted by Pasco et al., 2022 in the construction field, and in the work of Wilson et al., 2014 concerning repairing application in the power generation industry.

However, a comprehensive investigation into the material properties achievable in such cases is still lacking. Current studies have primarily focused on analyzing the properties of the fully LMD-w produces parts, without considering the manufacturing processes of real industrial components. LMD often introduce necessary interruptions in the deposition process due to geometrical or other constraints. Additionally, the comanufacturing case, where the final part includes both conventionally manufactured sections and AM sections, has not been adequately addressed in relation to its impact on material properties.

This work aims at characterizing the LMD-w process in terms of process stability and the material properties by investigating various process conditions. To achieve this, a comprehensive process development is performed, staring from the deposition of single tracks and progressing to multipass/multilayer components. Samples are produced using three representative process conditions, namely continuous deposition, interrupted deposition, and comanufacturing. Subsequently, the samples are characterized to assess their relative density, microstructure, and tensile properties.

2. Materials and methods

2.1. Materials

The feedstock utilized in this research consists of AISI 316L stainless steel, which is chosen due to its relatively good processability and ready availability. Its composition can be appreciated in the standard EN ISO 14343-A (nominal composition 19 12 3 L Si). As for substrates, SS 316L plates with a thickness of 10mm were employed. In the case of comanufacturing, the first half of the sample is represented by a machined 316L cylinder with 60mm diameter and a wall thickness of approximately 7mm.

2.2. LMD-w deposition cell

The experimental setup utilized in this study is based on a prototypal LMD-w cell (BLM Group, Cantù, Italy) known as Additube, currently installed at Politecnico di Milano. The system comprises a coaxial wire deposition head (CoaxPrinter) produced by Precitec (Precitec GmbH, Gaggenau, Germany) mounted on a 6-axis robot (IRB 4600 45/2.05, ABB Ltd, Zürich, Switzerland).

Two additional movement axes are provided by a positioner (IRBP A-250, ABB Ltd, Zürich, Switzerland). The laser source employed (YLS-3000-CUT, IPG Photonics, Oxford, USA) features a maximum power of 3kW. The system features a single motor wire feeder and a wire straightener.

2.3. Experimental procedure and sample characterization

The process development phase begins with a feasibility campaign focused on single-track. During this experimentation, the process parameters were varied following Table 1. The resulting depositions were qualitatively characterized as either successful or failed. Based on these evaluations, a process stability window was established and a selected set of parameters for single tracks were determined based on stability criteria.

Table 1. Single track feasibility campaign process parameters

Fixed parameters	**Value**
Material	SS 316L
Wire diameter (mm)	1.0
Variable parameters	**Value**
Laser power (W)	1250-1500-1750-2000
TCP speed (mm/s)	15-25-35-45
Wire speed (mm/s)	15-22.5-30-37.5

With the chosen set of parameters, single-tracks and single-layers were produced to estimate respectively the overlap and layer thickness parameters needed for multipass/multilayer components. The scan strategy employed for the single layers is dedicated to axisymmetric thick-walled (multipass) components, consisting of a round outer and inner finishing pass and spiral infill.

Based on the resulting process parameter, thick-walled multipass/multilayer cylinders were manufactured varying the process conditions. Three representative cases have been identified:

1. Continuous deposition: the entire sample was deposited in a single uninterrupted phase.
2. Interrupted deposition: half of the sample was deposited, followed by a process stoppage, and then the remaining half of the sample was deposited. This case represents situations in real industrial applications where process interruptions are necessary.
3. Comanufacturing: half of the sample is manufactured through machining, the second half is deposited with LMD-w. The case is representative of situations where additional features are added to an existing component, such as repair, or when the substrate becomes part of the final component.

The samples produced for the three different cases were characterized in terms of relative density, microstructure and tensile properties. Metallographic cross sections were obtained, and their image was acquired using an optical microscope. The EBSD technique was employed on the prepared cross section to investigate their microstructure. Relative density was computed through an image analysis software. Tensile samples were realized according to ASTM E8 standard and were subsequently tested using a tensile testing machine (Alliance RT/100, MTS Landmark®, Turin, Italy).

3. Results and discussion

3.1. Single track process window

Figure 1 shows the result of the analysis of the process stability and clearly identifies the process window, which increases with increasing power.

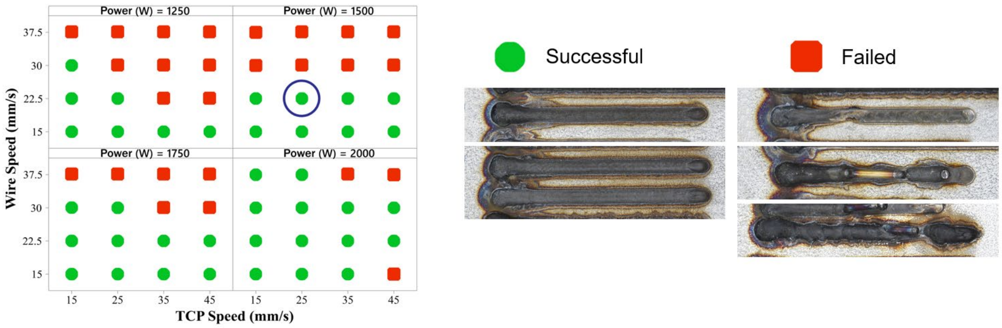

Fig. 1. Results of the single track process window analysis

Among the stable conditions, the process condition circled in blue has been chosen to account for tolerances regarding slight parameter variations expected during multipass/multilayer components processing. The choice of lower power within the tested range has been made to counterbalance the thermal build up expected during the fabrication of multilayer components.

3.2. Single track and single layer 3D measurement

Using the highlighted condition, singletracks and single layers were fabricated. Subsequently, 3D measurements were conducted to determine the overlap parameter and layer thickness. The overlap parameter was determined based on the width of the single track, while the layer thickness (Δz) was determined from the height of the single layer. The overlap was set as 50% of trackwidth, while Δz was set at 70% of the measured single layer height. These values align with the recommendations provided by the hardware manufacturer and are commonly reported in the literature. Figure 2 provides a schematic representation of the performed measurements.

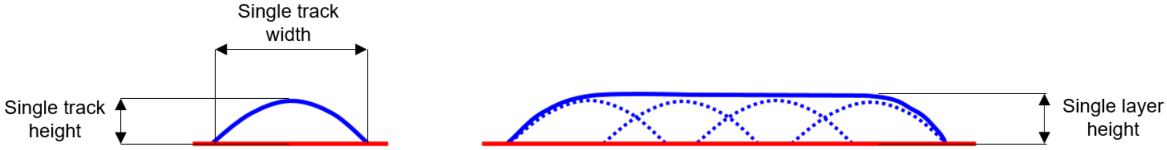

Fig. 2. Schematic drawing of the measurements performed

The results obtained from the measurements are presented in Table 2.

Table 2. Single track and single layer 3D measurements results

Type of deposition	**Height (mm)**	**Width (mm)**
Single track	0.47±0.02	2.23±0.10
Single layer	1.07±0.07	-

3.3. Production of multipass/multilayer components

The chosen set of process parameters used for the fabrication of multipass/multilayer components, following the aforementioned approach, is provided in Table 3 for reference.

Table 3. Parameters for the production of multipass/multilayer components

Parameter	**Value**
Material	SS 316L
Wire diameter (mm)	1.0
Laser power (W)	1500
Wire speed (mm/s)	22.5
TCP speed (mm/s)	25
Layer thickness, Δz (mm)	0.8
Overlap (mm)	1.1

The processing of the samples did not reveal process instabilities, hence it could be assessed that the process development performed was successful.

3.4. Relative density

The measurements performed on the AM part of each sample consistently demonstrated a relative density always exceeding 99.9%, suggesting complete consolidation of the sample irrespective the process conditions. The numerical results indicate a mean relative density of 99.94, 99.97 and 99.95 respectively for sample 1 – Continuous deposition, 2 – Interrupted deposition and 3 – Comanufacturing.

3.5. Microstructure

The EBSD microstructural analyses revealed the presence of large, elongated grains in the growing direction for sample 2 – Interrupted deposition and 3 – Comanufacturing. The similarity in their appearance suggests that there will be a minor difference in their mechanical properties. However, in the case of sample 3 – Comanufacturing the analysis of the junction region shows the transition from small equiaxed grains in the conventionally manufactured first half, to progressively larger elongated grains in the upper half. This varying microstructure indicates that a more substantial variation in properties is anticipated for sample 3.

3.6. Tensile tests

The conducted tensile tests demonstrated a ductile behavior across all the tested conditions. This conclusion is supported by both the stress-strain curves and the physical appearance of the fracture surfaces. Notably, the fracture location for sample 2 – Interrupted deposition and 3 – Comanufacturing never not coincide with the junction line between the two halves of the sample. This observation suggests the full bonding has been reached, indicating that the junction itself should not be considered as a critical point regarding mechanical properties. The stress-strain curves further indicate that sample 3 – Comanufacturing exhibits a notably different behavior compared to the other samples. It displays lower elongation but higher yield strength (YS) and ultimate tensile strength (UTS) values.

The numerical results reveal a mean YS of 253, 273 and 296 MPa, a mean UTS of 556, 570 and 596 MPa, a mean A% of 53, 49 and 39 respectively for sample 1 – Continuous deposition, 2 – Interrupted deposition and 3 – Comanufacturing. there is an increasing trend from sample 1 to 3 regarding YS and UTS, while A% decreases. The differences are quite limited between sample 1 and 2 while they become more relevant between sample 1 and 3. This observation is consistent with the stress-strain curves and the microstructural characterization.

The observed variations can be attributed to two main factors: the microstructural changes induced by the varying thermal cycles and the residual stresses resulting from the different processing conditions. In case of sample 2 and 3, the testing location is near the junction line between the two halves. As a result, the tested material has not been deposited in a steady-state condition, leading to the presence of non-uniform microstructure and residual stresses.

4. Conclusions

The present study aimed to investigate the feasibility of using Laser Metal Wire Deposition (LMD-W) for industrial components, considering the challenges associated with real processing conditions such as interruptions and comanufacturing. The research encompassed process development, starting from the evaluation of single track feasibility, progressing to the production of multipass/multilayer geometries, and analyzing them in terms of density and tensile properties. The key findings of this study are summarized as follows:

- The adopted process development strategy, which involved qualitative assessment of single tracks and the production of multipass/multilayer components, successfully yielded fully consolidated components while maintaining optimal process stability.
- The relative density of the AM part in each sample consistently exceeded 99.9%, confirming the full consolidation and the effectiveness of the process parameter investigation approach.
- The presence of a junction in samples 2 (Interrupted deposition) and 3 (Comanufacturing) did not serve as a weak point, as the fracture locations during the tensile tests were consistently different from the junction area.
- The tensile properties exhibited variations depending on the process conditions, with the most significant differences observed in sample 3 (Comanufacturing). These variations are likely attributed to microstructural changes and residual stresses. It is important to note that for more heat-sensitive alloys, these effects can become even more significant and should be thoroughly considered for industrial applications.

Further developments of this work involve conducting a more comprehensive characterization of the mechanical properties varying the processing conditions, including fatigue testing and the investigation of the presence of anisotropy. Furthermore, comparison of SS 316L with other alloys would provide a broader reference for materials selection in industrial component production.

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