Laser Metal Wire drop-by-drop Deposition: a material and dilution investigation

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Abstract. Additive Manufacturing has become a field of high interest in the industry, mostly due to its strong freedom of design and its flexibility. Numerous Additive Manufacturing techniques exist and present different advantages and disadvantages. The technique investigated in this research is a drop-by-drop deposition alternative to Laser Metal Wire Deposition. This technique is expected to induce a better control over the power input in the material, resulting in a better power efficiency and tailorable material properties. The aim of this research is to investigate selected material properties of the structures produced with the drop-by-drop deposition technique. Multi-drops structures were deposited from 316L, Inconel 625 (NW625) and AlSi5 (AW4043) wires. Two drop deposition methods were investigated: (i) a contactless recoil pressure driven detachment for 316L and Inconel 625, (ii) a contact-based surface tension driven detachment for AlSi5. A material characterization including optical microscopy, EDS and hardness measurements was performed in transverse and longitudinal cross-sections. The microstructure of the deposited material, the dilution with the substrate and the heat affected zone were analysed. The contactless detachment showed a higher dilution than the contact-based technique due to the laser irradiating the substrate between two drop detachments, which melts the substrate that then mixes with the deposited drops.

1. Introduction

Additive Manufacturing (AM) regroups numerous different techniques that offer different manufacturing possibilities and material properties. Certain AM techniques such as Laser Powder Bed Fusion or Electron Beam Powder Bed Fusion offer a high accuracy with a fine microstructure but also have a low building rate, while other techniques such as Directed Energy Deposition, Wire-Arc Additive Manufacturing (WAAM) and Laser Metal Wire Deposition (LMWD) offer a high building rate with a coarser microstructure and lower precision [1,2].

In regular LMWD, the wire is usually fed from the front and a defocused laser beam is used to melt both the wire and the substrate in a common melt pool that solidifies into a track [3]. One limitation of this process is that it is direction dependent. However, this direction dependence can be eliminated by using a coaxial wire feeding system where the laser beam is split coaxially to a vertically fed wire and focused at the intersection between the wire and the plate [4]. Another limitation of LMWD is that a consequent part of the laser beam energy is used to melt the substrate instead of the wire. In order to
improve the energy efficiency of the process, it has been showed that feeding an aluminium wire vertically and melting it with a laser beam few millimeters above the substrate could improve the energy efficiency [5]. In this case, the laser beam was used only to melt the wire, while the heat condition through the molten deposited material was enough to cause a sufficient remelting of the previous layer and guarantee a correct attachment.

The arc processes, such as arc welding and WAAM, have been further optimized by modulating the arc and the wire feeding, resulting in three different material deposition modes. The continuous arc mode consists of continuously feeding the wire with a continuous arc that melts both the wire and the substrate. The pulsed arc mode consists of continuously feeding the wire and pulsing the arc in order to detach one droplet from the wire for each arc pulse. The Cold Metal Transfer mode consists of pulsing the arc when the wire is at a high position to generate a droplet and detaching the droplet by feeding the wire, where the droplet detaches by contact with the melt pool, then the wire is retracted and a new arc pulse generates a new drop. These different improvements involving drop generation enabled to increase the energy efficiency and reduce the heat input in the substrate or previous layer, which is essential for building structures with WAAM [6,7].

While the wire-arc processes have been extensively improved, very little development has yet been achieved for wire-laser processes. The present study focuses on a drop-by-drop alternative to LMWD under development in a related research. This technique consists of depositing material drop by drop from the wire instead of continuously melting the wire with the substrate, where incremental wire feeding is applied to detach a drop and the laser power is kept constant. The drop generation from a metal wire with the help of the laser beam was first theorized and demonstrated by Kokalj et al. (2006) where it was called Laser Droplet Formation Process [8]. In this process, metal drops in a size range of 1 mm to 2 mm are generated by melting a wire with a low laser power, and they are detached by a high power laser pulse. In subsequent studies this technique was then called Laser Droplet Generation (LDG) and it has been used for multi-material joining of wires, foils and plates with nickel and silver droplets [9].

This research is dedicated to the material properties obtained with different drop-by-drop alternatives to LMWD, especially the dilution between the added material and the substrate. The chemical dilution has a limited importance in additively manufactured structures as it affects mostly the first layer [10]. However, it is a good indicator of the excess energy input that contributes to melting the substrate or the previous layer instead of melting the added material [11]. The dilution was found to be 10% to 30% with WAAM and about 8% with LWMD at optimized parameters [12,13]. The aim of this study is to analyze the dilution of the drops with the substrate and the material properties obtained in order to know if the present process with only incremental wire feeding is sufficiently energy efficient, or if laser power modulation should also be applied to increase the energy efficiency.

2. Methods

2.1. Process

Drop-by-drop LMWD experiments were carried out with two different techniques: a contactless technique where the drops are detached from the wire, fall and land in the track (Fig. 1a), and a contact-based technique where the drops detach by contact with the track (Fig. 1b). A laser beam was used to melt the tip of the wire into a droplet, of which the size was increased by feeding the wire through the laser beam, thus melting more material into the drop. The laser used was a 5 kW Ytterbium fiber laser and it was fed for a feeding length of 8 mm at 5 m/min through the laser beams of which the total power was 2 600 W (phase I in Fig. 2a). When the wire feeding stopped, the drop (which was about 2.6 mm
diameter) detached in the laser beam and landed on the substrate. After a short delay (phase 2 in Fig. 2a), the robotic arm was moved 2.5 mm forward to the next drop detachment position at the speed of 0.6 m/min (phase 3 in Fig. 2a). This technique was used to deposit 30-drop tracks from a 316L stainless steel wire and a NW6625 nickel alloy wire.

For the contact-based deposition technique, the wire was molten at 5 mm above the substrate (Fig. 1b) and it was fed for a feeding length of 20 mm at 15 m/min though the laser beams of which the total power was 5 000 W (phase 1 in Fig. 2b). The wire feeding stopped approximately when the drop

![Figure 1](image1.png)

**Figure 1.** a) Set up for the contactless deposition, b) setup for the contact-based deposition, c) laser beams profile on the wire.

![Figure 2](image2.png)

**Figure 2.** Representation of a drop deposition cycle for a) the contactless deposition technique, b) the contact-based deposition technique.
was large enough (about 3.5 mm diameter) to touch the substrate and detach by contact. After a short delay (phase 2 in Fig. 2b), the robotic arm was moved 3 mm forward to the next drop detachment position at the speed of 0.6 m/min (phase 3 in Fig. 2b). This technique was used to deposit tracks with up to 4 drops from an AlSi5 aluminium alloy wire. The contact-based deposition technique was developed specifically for aluminium alloys, since their thermodynamics properties and surface tensional properties under oxidation did not allow drop detachment with the contactless deposition technique.

Fig. 3 shows a high-speed imaging frame sequence for each of these two drop deposition methods when the drop detaches from the wire and attaches to the substrate. A specificity of the contactless method is that the laser beams irradiate the substrate between two drop generations (phases 2 and 3) which creates a melt pool in which the drops land (Fig. 3a). While with the contact-based method with aluminium, the laser beams irradiate the wire after each drop detachment, which does not directly create a melt pool on the substrate.

![Figure 3. High-speed imaging frame sequence of drop detachment and attachment with a) contactless deposition from a 316L wire, b) contact-based deposition from an AlSi5 wire.](image)

### 2.2. Material analysis

Three tracks were produced with three different materials commonly used in AM, of which the compositions are shown in Table 1. Two 30-drop tracks were deposited with the contactless technique from a 316L wire and a NW6625 wire on a DOMEX 350LA substrate. Two tracks (4-drop and 2-drop long) were deposited with the contact-based technique from an AlSi5 wire on a 1000 series aluminium substrate.

Longitudinal and transversal cross-sections were cut out of the tracks produced in order to analyze the three materials deposited with two different techniques. Optical microscopy was used to capture macro- and micrographs of the samples with different etchants. For the 316L and NW6625 samples, Klorpikrin etchant was used for the macrograph and Villela reagent was used for the micrograph. On the NW6625 sample, the substrate was masked in order to etch only the track. For the AlSi5 samples, Na-OH 20% was used for both the macro- and micrographs.

Energy-Dispersive X-ray Spectroscopy (EDS) measurements were taken on a vertical line crossing both the track and the substrate in order to measure the chemical composition throughout the tracks. Vickers hardness was measured on vertical lines crossing the track and the substrate, including the Heat Affected Zone (HAZ), where each measurement point was achieved with a 1 Kg load.

Two methods were investigated to calculate the dilution of the drops with the substrate. The first method consisted of using EDS to measure inside the tracks the average content of chemical elements that were originally present only in the wire and not in the substrate. For the 316L track, these targeted
elements were Cr, Ni and Mo, for the NW6625 track these elements were Cr, Ni, Nb and Mo and for the AlSi5 track the only targeted element was Si. Comparing the chemical contents of these elements measured in the track to the ones of the original wire gives the dilution ratio. The second method consisted of measuring on the transversal macrographs the track area above and below the substrate upper surface, where the area above the substrate represents the wire material added by drop transfer and the area below the substrate represents the substrate material molten during the process. The ratio of the area below the substrate to the total track area gives the dilution ratio.

**Table 1.** Chemical compositions (wt%) of the wires and substrates used.

|        | C   | Si  | Mn  | P   | S   | Cr   | Ni   | Mo  | Nb  | Zn  | Al  | Fe  |
|--------|-----|-----|-----|-----|-----|------|------|-----|-----|-----|-----|-----|
| 316L wire | 0.02 | 0.8 | 0.7 | -   | -   | 18.0 | 12.0 | 2.5 | -   | -   | -   | Bal. |
| NW6625 wire | 0.025 | 0.2 | 0.15 | ≤0.015 | ≤0.015 | 21.5 | 61 | 8.7 | 3.5 | - | - | 4 |
| AlSi5 wire | - | 5.0 | ≤0.05 | - | - | - | - | - | - | ≤0.1 | Bal. | ≤0.4 |
| DOMEX 350LA substrate | 0.10 | 0.040 | ≤0.90 | ≤0.030 | ≤0.025 | - | - | - | ≤0.1 | - | ≥0.10 | Bal. |
| 1000 series aluminium substrate | - | - | - | - | - | - | - | - | - | - | Bal. | 0.4 |

3. **Results**

3.1. *Stainless steel 316L deposited with the contactless technique*

Figure 4 shows the track produced with 316L and its material analysis. The different drops deposited are visible in the macrographs and a HAZ of 1 mm to 1.5 mm is visible in the substrate under the track (Fig 4b and c). The microstructure was bainitic in the two drops on both sides of the drop-to-drop interface (Fig. 4.d).

In Figure 4.c, it was measured that 46% of the track is above the substrate and 54% is below the substrate (white dashed line), which gives a dilution ratio of 54% in this cross-section. The line EDS measurements (yellow line in Fig. 4b) exhibited in Figure 4.e show an average chemical composition in the track of 9.5% Cr, 5.6% Ni, 1.4% Mo and 82% Fe. The Cr, Ni and Mo contents in the track are respectively 53%, 47% and 50% of the contents in the original wire (Table 1), which gives a dilution ratio of 47% to 53% in this measurement line.

However, the chemical composition is not exactly uniform in the track, the EDS measurement line crosses the upper part of drop n°20 and the lower part of drop n°19, which have slight variations of chemical composition (Fig. 4e). In this case, the upper part of drop n°20 contains 10.9% Cr, 6.4% Ni and 1.6% Mo, which is the result of a 39% to 47% dilution ratio with the substrate, while the lower part of drop n°19 contains 8.1% Cr, 4.8% Ni and 1.1% Mo which represents a 55% to 61% dilution ratio.

Figure 4f shows the line hardness measurements (blue line in Fig. 4b) crossing two different drops and the HAZ in the substrate. The hardness is relatively uniform in the track regardless of the drop change, with an average hardness value of 389 HV1. The hardness of the substrate outside the HAZ is about 138 HV1 while the hardness in the HAZ is about 152 HV1, so there might be a slight hardening in the HAZ.
Figure 4. Material characterization of the 316L track deposited with the contactless method, with: a) photography of the track as-built, b) macrograph of the longitudinal cross section, c) macrograph of the transversal cross-section, d) micrograph of the microstructure, e) line EDS measurement, f) line Vickers hardness measurement.

3.2. Nickel alloy NW6625 deposited with the contactless technique

Figure 5 shows the track produced with NW6625 and its material characterisation. The different drops are hardly visible in the macrographs, probably because of a different etching reaction to this chemical composition (Fig. 5b and c). The microstructure was austenitic (Fig. 5d).

In Figure 5c, 56% of the track is above the substrate and 44% below the substrate, indicating a dilution ratio of 44% in this cross-section. In the line EDS measurement shown in Figure 5e, the average chemical composition in the track is 9.4% Cr, 28% Ni, 1.7% Nb, 4.2% Mo and 56% Fe. The Cr, Ni, Nb and Mo contents are respectively 44%, 46%, 49% and 48% of the contents in the original wire (Table 1), which indicates a dilution ratio of 51% to 56% in this measurement line.

With NW6625, the chemical composition is also non-uniform in the track, which can be observe where the EDS measurements change from the upper part of drop nº24 to the lower part of drop nº23 (Fig. 5e). The upper part of drop nº24 contains 8.1% Cr, 25% Ni, 1.4% Nb and 3.7% Mo, which represents a 57% to 62% dilution with the substrate, while the lower part of drop nº23 contains 10% Cr, 29% Ni, 1.8% Nb and 4.4% Mo, which indicates a 49% to 53% dilution ratio.
Figure 5. Material characterization of the NW6625 track deposited with the contactless method, with: a) photography of the track as-built, b) macrograph of the longitudinal cross section, c) macrograph of the transversal cross-section, d) micrograph of the microstructure, e) line EDS measurement, f) line Vickers hardness measurement.

The line hardness measurements exhibited in Figure 5f show a very uniform hardness over the track that does not seem to be affected by the change of drop. The average hardness in the track is 158 HV1 while the average hardness in the substrate is 173 HV1.

3.3. Aluminium alloy AlSi5 deposited with the contact-based technique

Figure 6 shows the tracks produced with an AlSi5 wire and their material analysis. The different drops deposited are distinguishable in the macrographs with a Partially Melted Zone (PMZ) at the interface between two drops (Fig. 6c and d). The PMZ occurs when an aluminium alloy is heated between its liquidus and solidus temperature, where the eutectic phase is liquid and the primary α aluminium phase is still solid, it is commonly observable at interlayer interfaces in additively manufactured structures [5].
The microstructure of the track in Figure 6.e shows tightly packed primary $\alpha$ aluminium dendrites (bright regions) separated by a thin eutectic phase (dark mesh). It can be noted that numerous pores are present inside the material (black dots in Figure 6c and d), their spherical shape indicate that they are most likely gas pores.

In figure 6d, 72% of the track is above the substrate and 28% is below the substrate, thus the dilution with the substrate is about 28% in this cross-section. In Figure 6f, the line EDS measurements show that the average chemical composition in the track is 4.3% Si and 95.7% Al. The Si content in the track is 86% of the content in the original wire (Table 1), thus the dilution with the substrate is about 14% in this cross-section.

Figure 6. Material characterization of the AlSi5 tracks deposited with the contact-based method, with: a) photography of the 4-drop track, b) photography of the 2-drop track, c) macrograph of the longitudinal cross section, d) macrograph of the transversal cross-section where the black dots are gas porosities, e) micrograph of the microstructure, f) line EDS measurement, g) line Vickers hardness measurement.
In this track, no difference of chemical composition was observed from one drop to another. However, there seem to be a small decrease of Si content in the PMZ, where it is 3.8% compared to 4.4% outside of the PMZ. This decrease of Si content in the PMZ is most likely due to the partial dilution of the liquid eutectic phase present in the PMZ (containing most of the Si) with the newly added liquid drop.

The hardness measured in the track is relatively uniform with an average value of 52 HV1, while the average hardness measured in the substrate is 30 HV1, where there seem to be a softening effect close to the deposited drops (Fig. 6g).

4. Discussion

The two methods investigated to measure the dilution showed some variations of results that could be attributed to the different locations where the measurements were taken. Relatively small variations of chemical composition (thus dilution) were observed from one drop to another with the contactless deposition technique. 316L and NW6625 showed inverse variations of composition from the upper part of a drop to the lower part of another drop. It means that these are most likely not variations within the lower part and upper part of a same drop but rather variations from one drop to another. These variations of dilution might depend on the landing conditions of the drops, especially their contact area with the pre-existing melt pool. This effect could be reduced by improving the accuracy of drop positioning. However, the hardness properties were not affected by these local changes of chemical compositions, thus it might not have a considerable effect on the final mechanical properties.

Overall, it is noticeable that the contactless deposition technique investigated with 316L and NW6625 induces considerably more dilution than the contact-based deposition technique investigated with AlSi5. This is very likely due to melt pool generated by the laser beam on the substrate between two drop detachments with the contactless technique. Such a large melt pool might not be required for the drop attachment, it was shown in this study that it induces an extensive dilution between the drop and the substrate, and it might also induce too much remelting of the previous layer when building AM structures. Thus, a next development step will be apply laser power modulation to this process, for instance by reducing the laser power during phases 2 and 3 (Fig. 2), which will also reduce the energy consumed by the process.

5. Conclusions

In the present study where two drop-by-drop deposition techniques were investigated with three different materials, the following conclusions can be drawn:

- The contactless drop deposition technique with 316L and NW6625 involved a melt pool formed with approximately the same quantity of material molten from the substrate as in the added drops, with a dilution of 44% to 56%. This is due to the laser beam irradiation on the substrate between two drop depositions with the contactless technique. Such a large melt pool might not be required for the drop attachment, it was shown in this study that it induces an extensive dilution between the drop and the substrate, and it might also induce too much remelting of the previous layer when building AM structures. Thus, a next development step will be apply laser power modulation to this process, for instance by reducing the laser power during phases 2 and 3 (Fig. 2), which will also reduce the energy consumed by the process.

- The contact-based deposition technique with AlSi5 involved a lower dilution with the substrate, of about 14% to 28%, because the laser beam does not act on the substrate and no melt pool is actively formed for the drops dilute with. The small quantity of substrate molten is due to the heat conduction through the aluminium drop after landing. Many gas pores are present in the material, which could be due to the technique used or to the material.

- The contactless drop deposition with 316L and NW6625 showed a difference of dilution from one drop to another of 16% to 35%. It is most likely due to slightly different landing positions of the drops, resulting in different contact areas with the melt pool, which induces a difference of mixing between the drop and the melt pool. While the contact-based drop deposition with AlSi5 showed a homogeneous chemical composition throughout a drop with a localised
decrease of silicon content in the partially melted zone, probably due to the mixing of the liquid eutectic phase with the newly deposited drop.

- While the dilution induced by the contact-based deposition technique can be acceptable, the contactless technique in its current development stage results in a too high melting of the substrate which cause a high dilution. Incremental wire feeding with constant laser power might result in a too high power input in the deposited material. As a next step, laser power modulation should be applied in order to reduce the heat input between two drop depositions and increase the process efficiency.

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References

[1] Frazier W E 2014 Metal additive manufacturing: A review J. Mater. Eng. Perform. 23 1917–28
[2] Lewandowski J J and Seifi M 2016 Metal Additive Manufacturing: A Review of Mechanical Properties Annu. Rev. Mater. Res. 46 151–86
[3] Heralić A 2012 Monitoring and Control of Robotized Laser Metal-Wire Deposition (Göteborg: Chalmers University of Technology)
[4] Heralić A, Christiansson A K, Ottosson M and Lennartson B 2010 Increased stability in laser metal wire deposition through feedback from optical measurements Opt. Lasers Eng. 48 478–85
[5] Da Silva A, Wang S, Volpp J and Kaplan A F H 2020 Vertical laser metal wire deposition of Al-Si alloys Procedia CIRP 94 341–5
[6] Derekar K S, Addison A, Joshi S S, Zhang X, Lawrence J, Xu L, Melton G and Griffiths D 2020 Effect of pulsed metal inert gas (pulsed-MIG) and cold metal transfer (CMT) techniques on hydrogen dissolution in wire arc additive manufacturing (WAAM) of aluminium Int. J. Adv. Manuf. Technol. 107 311–31
[7] Frotevarg J, Kaplan A F H and Lamas J 2014 Comparison of CMT with other arc modes for laser-arc hybrid welding of steel Weld. World 58 649–60
[8] Kokalj T, Klemenčič J, Mužič P, Grabcic I and Govekar E 2006 Analysis of the laser droplet formation process J. Manuf. Sci. Eng. Trans. ASME 128 307–14
[9] Govekar E, Jerič A, Weigl M and Schmidt M 2009 Laser droplet generation: Application to droplet joining CIRP Ann. - Manuf. Technol. 58 205–8
[10] Li C, Gu H, Wang W, Wang S, Ren L and Wang Z 2020 Effect of Heat Input on Formability, Microstructure, and Properties of Al–7Si–0.6Mg Alloys Deposited by CMT-WAAM Process Appl. Sci. 10
[11] Demir A G and Biffi C A 2019 Micro laser metal wire deposition of thin-walled Al alloy components: Process and material characterization J. Manuf. Process. 37 362–9
[12] Lin Z 2019 Wire and Arc Additive Manufacturing of Thin Structures Using Metal-Cored Wire Consumables (Delft: Delft University of Technology)
[13] Abioye T E, Folkes J and Clare A T 2013 A parametric study of Inconel 625 wire laser deposition J. Mater. Process. Tech. 213 2145–51