EFFECT OF FILLER WIRE POSITION ON MATERIAL TRANSFER IN OFF-AXIS LASER WIRE DED (DIRECTED ENERGY DEPOSITION)

LISÄAINELANGAN SYÖTTÖSIJAINTIEN VAIKUTUS MATERIAALIN SIIRTYMISEEN OFF-AKSIAALISESSA SUORAKERROSTUKSESSA LASERILLA JA LANGALLA

Lappeenranta–Lahti University of Technology LUT

Bachelor’s Programme in Mechanical Engineering, Bachelor's thesis

2022

Leevi Hämäläinen

Examiner: Ilkka Poutiainen D.Sc (Tech)

ABSTRACT

Lappeenranta–Lahti University of Technology LUT

LUT School of Energy Systems

Mechanical Engineering

Leevi Hämäläinen

Effect of filler wire position on material transfer in off-axis laser wire DED (Directed Energy Deposition)

Bachelor's thesis

2022

25 pages, 12 figures and 5 tables

Examiner: Ilkka Poutiainen D.Sc (Tech)

Keywords: Additive manufacturing, deposition, DED, laser, wire, position

Behavior of filler material in the additive manufacturing process of directed energy deposition is investigated in this thesis. The objective was to research the effect on filler material transfer when changing filler wire feed positions. Prior research has not utilized a monitoring system to gather data on material transfer. This thesis consists of a literature review and an experimental part.

A directed energy deposition machine that melts filler wire using a laser was used in the experimental part. Front feeding, rear feeding and side feeding were used as the filler wire feeding positions. The filler wire was directed to the trailing edge of the laser spot. The monitoring data was used to analyze the behavior of filler material during the process. The tracks for each run were analyzed afterwards.

A U-shape was observed in the melt pool for front feeding of filler wire. The melt pool shape for side feeding of filler wire was asymmetric. However, no major differences in the tracks were observed. This suggests that off-axis directed energy deposition could be used to manufacture parts that require movement of the deposition head in multiple directions.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

LUT Energiajärjestelmät

Konetekniikka

Leevi Hämäläinen

Lisäainelangan syöttösijantien vaikutus materiaalin siirtymiseen off-aksiaalisessa suorakerrostuksessa laserilla ja langalla

Konetekniikan kandidaatintyö

2022

25 sivua, 12 kuvaa ja 6 taulukkoa

Tarkastaja: TkT Ilkka Poutiainen

Avainsanat: Lisäävä valmistus, suorakerrostus, DED, laser, lanka, syöttösijainti

Kandidaatintyössä tutkittiin lisäaineen käyttäytymistä lisäävän valmistuksen alalla olevassa suorakerrostusprosessissa. Tutkimuksessa pyrittiin selvittämään lisäainelangan syöttösijaintien vaikutusta lisäainemateriaalin siirtymiseen levyyn. Aikaisemmissa suorakerrostuksen lisäainelangan syöttösijainteja käsittelevissä tutkimuksissa ei ole käytetty monitorointilaitetta datan keräämiseen. Työ koostuu kirjallisuuskatsauksesta ja kokeellisesta osuudesta.

Kokeellisessa osuudessa käytettiin suorakerrostuslaitetta, joka sulattaa lisäainelankaa laserilla. Laserpisteen takareunalle kohdistettua lankaa syötettiin vuorollaan laserin edestä, takaa ja sivuilta. Monitorointidatasta analysoitiin materiaalin käyttäytymistä prosessin aikana. Prosessin jälkeen tutkittiin jokaisen syöttösijainnin tuottamaa palkoa.

Lisäainelangan etusyötöllä huomattiin U-muotoa sulassa. Sivusyötöllä sulan huomattiin olevan epäsymmetrinen. Tuotetuissa paloissa ei kuitenkaan huomattu suuria eroja. Tämä viittaa siihen, että off-aksiaalista suorakerrostusta on mahdollista käyttää sellaisten kappaleiden valmistamiseen, jotka vaativat suorakerrostuslaitteen ajamista useampaan eri suuntaan.

ABBREVIATIONS

AM	Additive Manufacturing
CAD	Computer-Aided Design
DED	Directed Energy Deposition

Table of contents

1 Introduction

Additive manufacturing (AM) is a manufacturing process in which parts are manufactured by applying material onto cross-sectional slices of a three-dimensional model. Material is added layer by layer to build the part. Typically, the model is created using computer-aided design (CAD) software. (Dutta, Babu, Jared 2019, p. 2; Gibson et al. 2021, p. 1–2.) Conventional manufacturing methods rely on subtractive or formative methodologies, whilst AM relies on joining raw materials to create parts directly from 3D model data (International Organization for Standardization 2016a, p. 5). In the ISO/ASTM 52900:2021-standard additive manufacturing is divided into seven different processes: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization. (International Organization for Standardization 2021, p. 2–3.) The following chapters describe additive manufacturing and the directed energy deposition processes in detail. Lastly the research problem and objectives are presented.

1.1 Additive manufacturing process

The first step in the additive manufacturing process is the creation of a three-dimensional model using CAD software (Gibson et al. 2021, p. 4). The model is converted into an STL file which contains a description of the surface geometry (Gibson et al. 2021, p. 5; International Organization for Standardization 2021, p. 6). The STL file is inserted into the AM machine and the machine parameters are set up for the build process. After this, the automated build process is started. Once the process is finished, the part is removed from the AM machine and post processed if required. (Gibson et al. 2021, p. 5–6.)

1.2 Directed energy deposition

Directed energy deposition (DED) is a form of additive manufacturing in which a focused source of thermal energy is used to melt materials as they are deposited (International Organization for Standardization 2016b, p. 11). Material is deposited onto cross-sectional slices of a CAD model and simultaneously melted by a focused thermal energy source (Dutta et al. 2019, p. 6; Gibson et al. 2021, p. 285–286). A typical DED machine consists of a thermal energy source, filler material feeder, shielding gas, and a robot for movement. The movement may be achieved by moving the deposition head, the substrate or both. (Gibson et al. 2021, p. 286–288.)

Energy sources in DED include laser, electron beam and plasma arc (International Organization for Standardization 2016b, p. 11). Gibson (2021, p. 292, 301) states that in addition to plasma arc, electric arc is also used as an energy source. Gibson (2021, p. 303–304) states friction stir may also be categorized as an energy source for DED due to it sharing more features with DED than any other AM method. Benefits for lasers as an energy source include a large energy density with a small heat-affected zone (Dávila et al. 2020, p. 3379). Electron beams are more efficient than lasers in the conversion of electrical energy to a beam (Gibson et al. 2021, p. 298–299). Another benefit to using an electron beam is the higher deposition rates that can be achieved. A disadvantage to electron beams is that they require a vacuum to operate in, which increases costs. (Dávila et al. 2020, p. 3380.) Arc as the source of thermal energy is a cheaper alternative to laser and electron beam (Gibson et al. 2021, p. 301; Milewski 2017, p. 93). Arc however has disadvantages such as a large heat affected zone and process control difficulties (Gibson et al. 2021, p. 301). Milewski (2017, p. 93) states that another disadvantage for arc processes is the inability to tightly focus the beam, which has a negative effect on accuracy.

Filler material is typically metal in powder or wire form (Gibson et al. 2021, p. 285; International Organization for Standardization 2016b, p. 11). Gibson (2021, p. 285) states that metals are the most common filler materials in DED, however it is possible to use non-metallic materials such as polymers, ceramics, and metal matrix composites. Filler material may be fed coaxially or off-axis to the energy beam (Gibson et al. 2021, p. 291). According to Brandl et al. (2011, p. 4665), benefits for using wire as filler material include “high deposition efficiency, high deposition rate, good availability and simplified handling and storage”. Using powder as filler material enables the creation of smaller layer thicknesses and widths which are not achievable by using wire. Powder is however more difficult to manufacture and store, more expensive, and less efficient due to powder losses during the DED process. (Demir 2018, p. 9.)

1.3 Research problem and objectives

The aim of this thesis is to gather data on filler material transfer in a directed energy deposition process. This thesis consists of a literature review on additive manufacturing and directed energy deposition, and an experimental part. In the experimental part an off-axis laser wire DED machine is run using different filler wire positions. Slight differences in the melt pools for different filler wire positions were observed from the monitoring data. From visually inspecting the tracks, no major differences in the tracks were observed for the different filler wire positions. The findings of this thesis are important as they suggest that off-axis DED machines may be used to produce parts which require moving the DED machine in multiple directions. This research is important due to the rising interest in researching DED, which can be seen from figure 1.

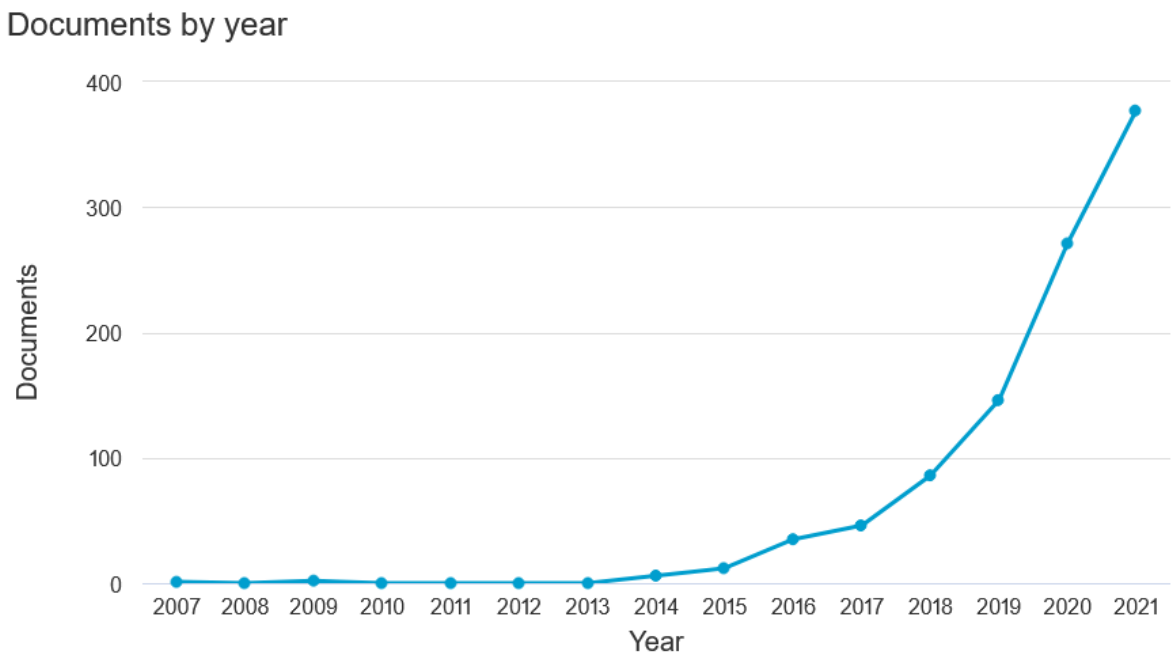


Figure 1. Scopus documents with “directed energy deposition” in the title, per year from 2007 to 2021. (Scopus 2022)

Prior research has studied the effect of rear and front feeding on track properties in off-axis DED. Syed and Li state that the best performance was obtained by using front feeding and placing the filler wire at the leading edge of the melt pool. By positioning the filler wire at the trailing edge of the melt pool, a better-quality track for rear feeding was achieved whilst imperfections in the front feeding track were observed. (Syed, Li 2005, p. 521–523.)

Prior research has not studied the effect of side feeding of wire on material transfer in off-axis DED. Also, previous research has not utilized a monitoring system to gather data on material transfer during the process. This thesis aims to fill the gap in research and provide data on the transfer of material using front, rear, and side feeding of filler wire. This thesis aims to answer the following research questions:

1. How does the change in filler wire position affect material transfer to the build surface?
2. How does filler wire position affect the tracks produced?

The scope of this thesis is limited to off-axis DED using wire as filler material and a laser as the source of thermal energy.

2 Methods

This chapter explains the procedure and methods for the experimental part in detail to ensure repeatability. The data-analysis methods are also reviewed.

2.1 Research methods for the experimental part

Information on material transfer in the off-axis laser wire DED process was gathered through a laboratory experiment in the LUT-laser processing laboratory. An off-axis laser wire DED machine was used to create tracks for different filler wire positions. Filler wire positions used in the experiment were for front feeding, rear feeding and side feeding on both sides. The aim of the experiment was to gather data on the effect different filler wire positions have on material transfer. Information on material transfer at different filler wire positions was gathered through the monitoring data and through visual analysis of the tracks and track dimensions.

2.1.1 Qualitative methods

The monitoring system provides qualitative data in the form of still images of the DED process. These images are visually analyzed for differing properties in material transfer between different filler wire positions. The physical dimensions and shape of the tracks are also measured and analyzed. The findings are compared to prior research.

2.1.2 DED setup

A DED machine with a laser as the thermal energy source was used in the experimental part. Filler wire was fed off-axis from the laser beam and directed towards the trailing edge of the laser spot. A monitoring system consisting of a high-speed camera and an illumination laser was installed next to the wire nozzle and laser beam. A labeled image of the DED setup is presented in figure 2. The entire DED machine is presented in figure 3.

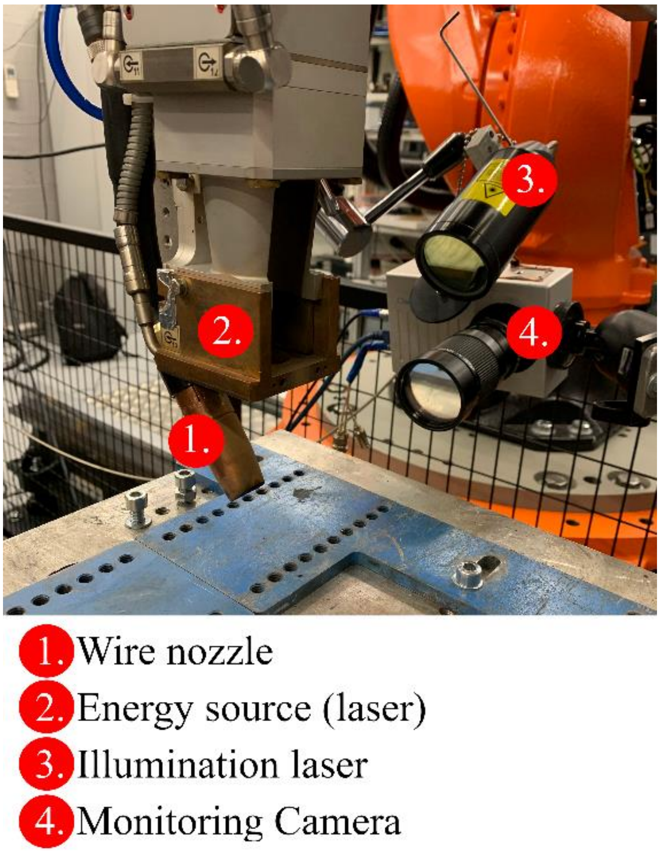


Figure 2. Deposition head and monitoring system with labels.

Figure 3. Image of the entire DED setup, with the deposition head connected to the KUKA robot.

The KUKA robot in figure 3 was utilized for moving the DED setup to create the tracks. The movement speed of the deposition head was set at 0.8 m/min. The build surface is also visible in figure 3 under the deposition head. The build surface was 20 mm thick s355 structural steel.

The DED machine used an IPG YLS 10 kW ytterbium fiber laser as the energy source. Parameters for the laser are displayed in table 1 and the laser parameters set for the experimental procedure are displayed in table 2. The wavelength for the laser was 1070 nm and the laser power was set to 3.4 kW. The focal point was set below the build plate at -50 mm. The laser was set perpendicular to the build plate.

Table 1. YLS-10000 laser parameters (IPG Photogenics Corporation)

Parameter	Value
Wavelength, nm	1070 ± 10
Mode of operation	CW/modulated
Modulation frequency, kHz	0-5
Maximum average power, kW	10

Table 2. Laser parameters set for the experimental part

Parameter	Value
Set power, kW	3.4
Focal point, mm	-50
Angle of laser	Perpendicular to plate

Table 3 describes the properties of the OK Aristorod 12.50 wire used in the experiment. The diameter of the wire was 1 mm, and it was fed at a 38-degree angle from the vertical axis. The wire was placed on to the trailing edge of the laser spot, as shown in figure 4. The feed rate was set at 2.5 m/min.

Table 3. Wire parameters

Parameter	Value
Type	OK Aristorod 12.50
Diameter, mm	1
Angle, degrees from vertical axis	38
Placement on laser spot	Trailing edge, as shown in figure 4
Feed rate, m/min	2.5
Shielding gas	Argon

A Cavitar Cavilux HF diode laser emitting an 808 nm wavelength was used for illuminating the process. The process was monitored using an Optronics CT 3000 high-speed camera with a Computar 55 mm telecentric lens. A passthrough filter was used on the camera to filter unwanted wavelengths and allow the wavelength of the illumination system through.

2.1.1 Experimental runs

The monitoring system was adjusted to minimize overexposure and to provide clear and focused images of the transfer of filler material. Using data from the monitoring system, the DED machine parameters were optimized to create a reproducible track.

Experimental runs for front, rear and side feeding were run once the DED machine and monitoring system were optimized. Data was gathered for each run using the monitoring system. The dimensions and shapes of the tracks were measured afterwards using a Keyence 3D measurement system.

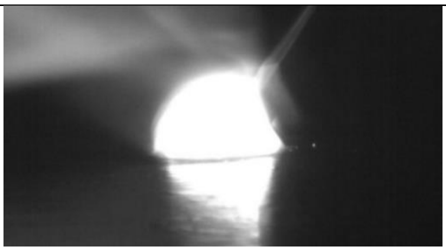
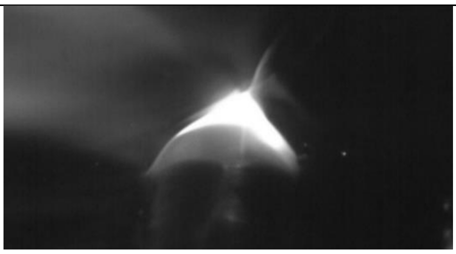
Finally, an analysis of the monitoring system data and the track dimensions and shapes was conducted. The dimensions and shapes of track were explained using data from the monitoring system. The monitoring system data was also used to analyze the melt pool shape.

3 Results

This chapter presents the key findings from the experimental part. Images extracted from the monitoring data are presented for each filler wire feeding position. The shapes and dimensions of the tracks are also presented.

Monitoring data for each filler wire feeding position is presented in table 4.

Table 4. Images extracted from monitoring data, displaying the DED process.

Filler wire position	Image
Front feeding	
Rear feeding	
Side feeding (towards camera)	
Side feeding (away from camera)	

In all images presented in table 4, the melt pool and filler wire are visible. The melt pool appears as a bright white colored area in the image. In all images the filler wire can be seen being fed form the top right of the image. In the images for front feeding, rear feeding and side feeding away from the camera, the track can be seen as a dark grey track attached to the melt pool. In the side feeding run towards the camera the track cannot be seen as the melt pool obstructs visibility.

The location of the laser spot is indicated with a purple line in figure 4. The filler wire is indicated with a blue line.

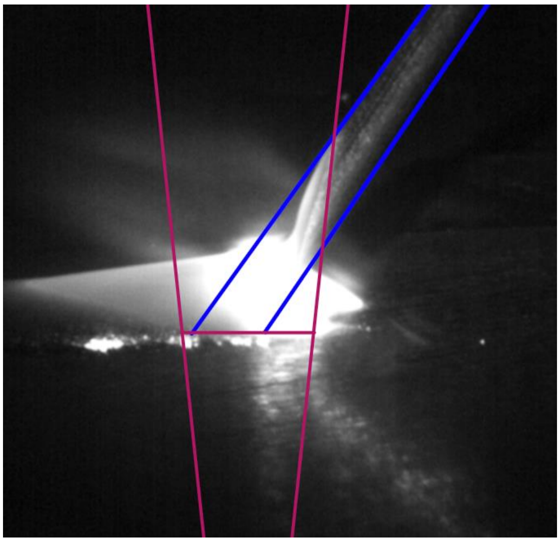


Figure 4. Position of the laser and wire drawn onto a monitoring image.

The filler wire was positioned onto the trailing edge of the melt pool which is seen from figure 4. The radius of the laser spot was calculated from PRIMES laser diagnostics software data, which provided the focal point of the laser and laser spot radiuses for multiple points along the beam. The data from PRIMES was inserted into a spreadsheet presented in figure 5 and continued linearly to get the laser spot radius at the surface of the build plate.

Position Z	Distance from focal (mm)	Radius (mm)	Focal point (mm)
38,64	10,458	0,385	49,098
34,09	15,008	0,514	
29,55	19,548	0,636	
25	24,098	0,785	

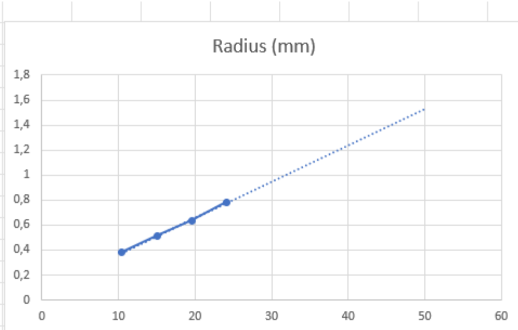


Figure 5. Laser spot radius calculation from PRIMES laser diagnostics software data.

The graph in figure 5 was used to estimate the radius of the laser spot. The radius for the laser spot was estimated to be 1.5 mm.

The shapes and dimensions of the tracks are presented in figures 6 and 7. Figures 6 and 7 were obtained by scanning the tracks with a Keyence 3D measurement system. The filler wire is fed from the top left in the tracks presented in figure 7.

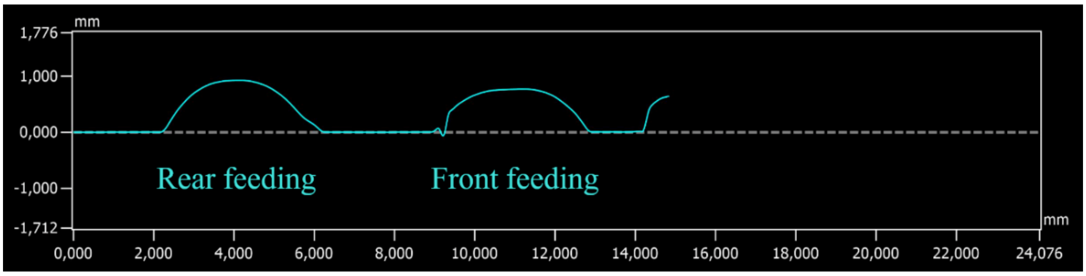


Figure 6. 3D measurement of the rear and front feeding tracks

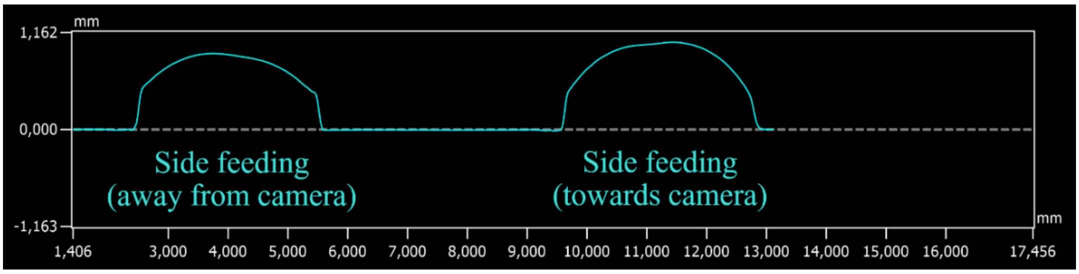
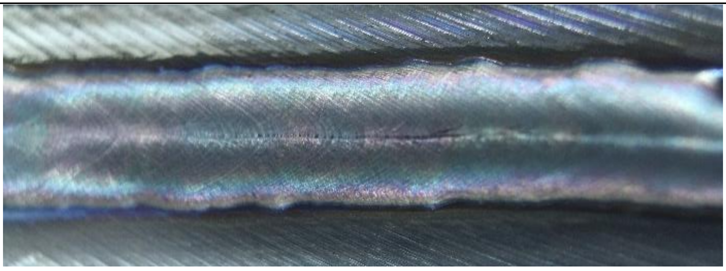
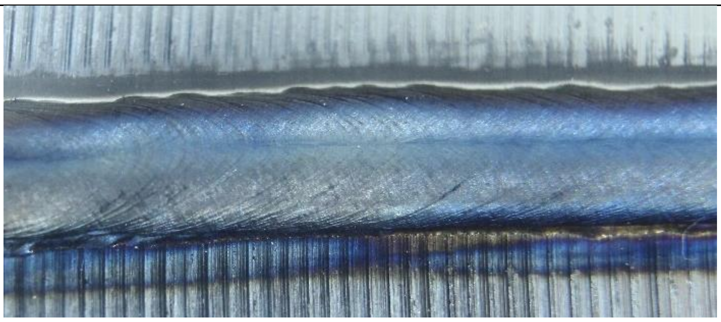


Figure 7. 3D measurement of the side feeding tracks

Each individual track was also photographed. Close up images of the tracks are presented in table 5.

Table 5. Close up images of the tracks

Front feeding	
Rear feeding	
Side feeding away from camera	
Side feeding towards camera	

The images in table 5 were used to analyze the uniformity of the tracks. The images are compared to each other to gather data on the effect of filler wire position on the track.

4 Analysis

The results from chapter 3 are analyzed with the aim of observing differences in material transfer and track properties for the different filler wire positions. A short discussion on the results and analyses is also presented.

4.1 Analysis of the results

In the front feeding of filler wire, a melt pool with a U-shape around the filler wire was observed. In figure 8, the monitoring image of front feeding is presented along with a binary image with only the melt pool being displayed.

Figure 8. Image extracted from the monitoring system for front feeding of filler wire (left). A binary image of the image on the left, which shows the melt pool (right).

From the binary image presented in figure 8, a clear U-shape is observed in the melt pool where the filler wire contacts the melt pool. Some of the wire melts immediately on contact with the laser beam, while the rest melts on contact with the melt pool.

The image for rear feeding and a binary image showing the melt pool are displayed in figure 9. Figure 9 shows that most of the wire in rear feeding melts on contact with the melt pool. The wire melting from contact with the laser beam is not as visible as in front feeding in figure 8.

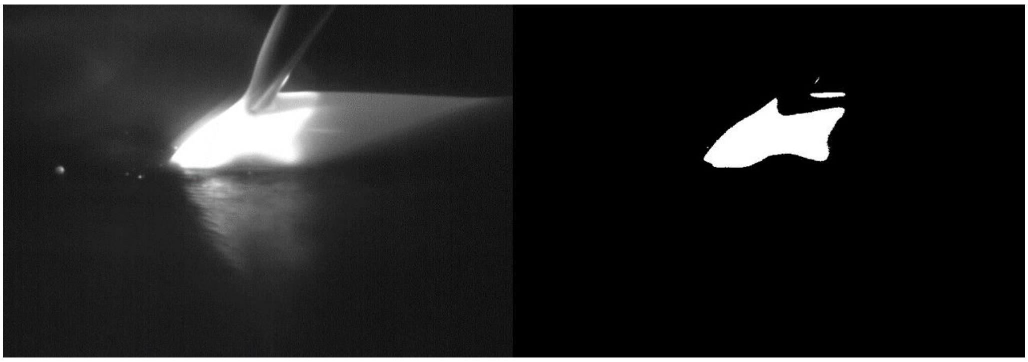


Figure 9. Rear feeding of filler wire (left). A binary image of the image on the left showing the melt pool (right).

In figures 10 and 11 the images for both side feeding runs are shown along with binary images that show the melt pool.

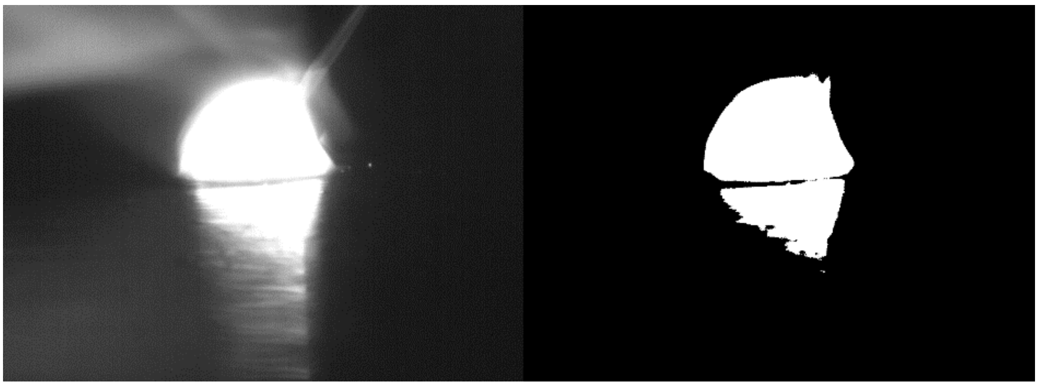


Figure 10. Side feeding of filler wire towards the camera (left). Binary image of the image on the left showing the melt pool (right).

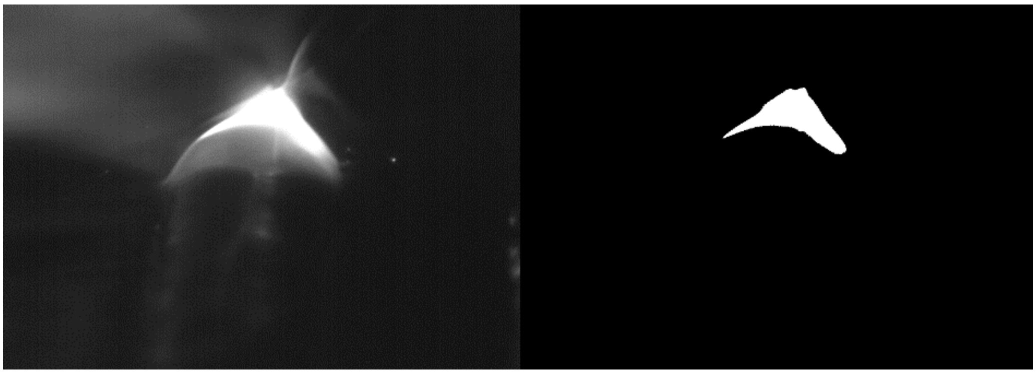


Figure 11. Side feeding of filler wire away from the camera (left). Binary image of the image on the left showing the melt pool (right).

The melt pools were observed to be asymmetric in both side feeding runs. In figure 10, the melt pool is observed to be larger on the opposite side from the filler wire. In figure 11 the top of the melt pool is positioned more towards the filler wire.

From photos of the tracks in table 5, an observation was made that although there are differences in melt pool shapes during the DED process, there are only slight differences in the track properties when using different filler wire positions. A less uniform edge in the track was observed in the front feeding of filler wire in comparison to rear and side feeding. These findings are in line with previous findings as Syed states that when placing the filler wire at the trailing edge of the melt pool, imperfections in the track were observed for front feeding whilst rear feeding was able to achieve a good quality track (Syed, Li 2005, p. 521–523).

Track widths and heights were estimated by calculating the number of pixels in the given scale and counting the number of pixels in the tracks. The estimations for track widths and heights are presented in figure 12.

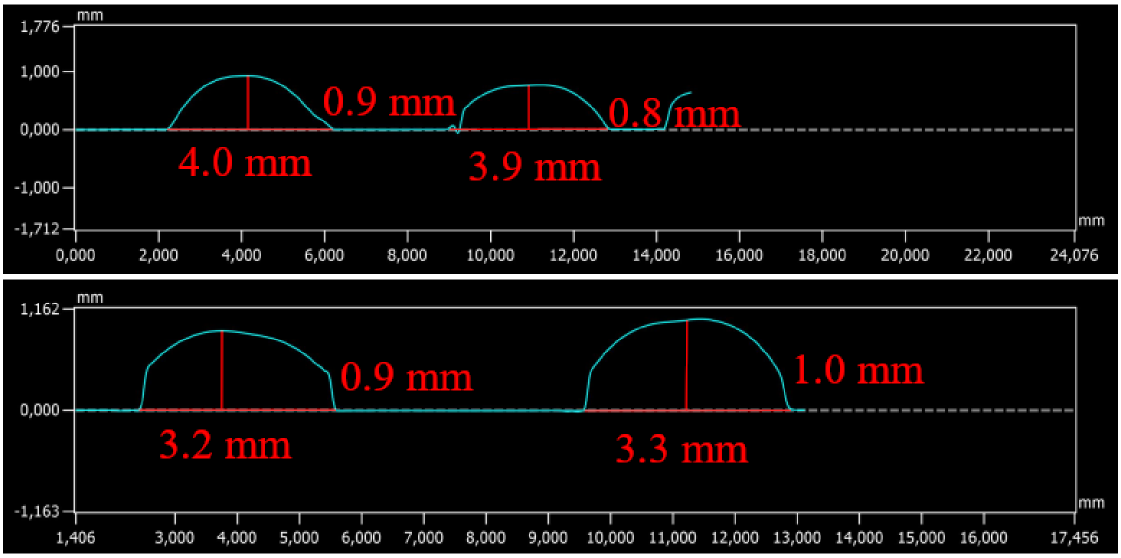


Figure 12. Heights and widths of the tracks. Top left: front feeding, top right: rear feeding, bottom left: side feeding away from the camera, and bottom right side feeding towards the camera.

The track shapes for each filler wire position were similar. The track heights ranged from 0,8 mm to 1 mm and track widths from 3,2 mm to 4 mm. Front and rear feeding of filler wire resulted in wider tracks than tracks from side feeding. Differences in track height were minimal. According to Gibson (2021, p. 292), the surface areas of the tracks should be similar due to the minimal material losses when using wire as filler material.

4.2 Discussion

The findings in this research were in line with previous research by Syed. The edge of the track for front feeding was less uniform and straight than those for rear and side feeding. Research by Syed also observed a good quality track when placing the wire at the trailing edge of the melt pool in rear feeding (Syed, Li 2005, p. 523.). In the experimental part all tracks were observed to be similar to each other with a slightly more uneven and less straight edge in the track for front feeding.

Different filler wire positions produced similar tracks, which suggests that off-axis DED could be used to manufacture parts which require movement of the deposition head in multiple directions. The repeatability of the experiment was ensured by keeping all parameters constant except for the filler wire feeding position.

5 Conclusions

There has been little research on the effect on material transfer at different filler wire feeding positions. This thesis consisted of a literature review on additive manufacturing and directed energy deposition. An experimental part was also conducted at the LUT-laser processing laboratory, in which an off-axis DED machine was monitored using different filler wire feeding positions. This thesis aimed to fill the gap in research on material transfer in off-axis DED at different filler wire positions.

An experimental part was conducted with the objective of monitoring an off-axis DED process to gather data on material transfer at different filler wire positions. Experimental runs for the feeding of filler wire from the front, rear and both sides were conducted. Data was gathered using a monitoring system consisting of a high-speed camera with a passthrough filter and a laser illumination system. The data from the monitoring system was analyzed visually. The tracks were measured using a 3D measurement system and the widths and heights of each track were calculated.

In front feeding of filler wire a U-shape in the melt pool was observed where the wire meets the melt pool. The melt pools in the side feeding of filler wire appeared to be asymmetric. However, no major differences in the track shapes were observed. Front and rear feeding of filler wire resulted in wider tracks than in side feeding. All tracks produced were similar, with the exception that the front feeding track had a more uneven edge in comparison to other feeding directions. The findings in this research suggest that off-axis DED may be a viable manufacturing method for parts which require the movement of the deposition head in multiple directions.

References

Brandl E, Palm F, Michailov V, Viehweger B, Leyens C (2011) Mechanical properties of additive manufactured titanium (Ti–6Al–4V) blocks deposited by a solid-state laser and wire. *Materials in Engineering* 32(10): 4665-4675.

Dávila JL, Neto PI, Noritomi PY, Coelho RT, da Silva J,Vicente Lopes (2020) Hybrid manufacturing: a review of the synergy between directed energy deposition and subtractive processes. *International Journal of Advanced Manufacturing Technology* 110(11-12): 3377-3390.

Demir AG (2018) Micro laser metal wire deposition for additive manufacturing of thin-walled structures. *Optics and Lasers in Engineering* 100: 9-17.

Dutta B, Babu S , Jared BH, (2019) *Science, Technology and Applications of Metals in Additive Manufacturing.* San Diego: Elsevier.

Gibson I, Rosen D, Stucker B , Khorasani M, (2021) *Additive Manufacturing Technologies.* Cham, Switzerland: Springer.

International Organization for Standardization (2021) Additive manufacturing. General principles. Fundamentals and
vocabulary (ISO/ASTM 52900:2021).

International Organization for Standardization (2016a) *Additive Manufacturing. General Principles. Part 3: Main
Characteristics and Corresponding Test Methods (ISO 17296-3:2016).*

International Organization for Standardization (2016b) *Additive Manufacturing. General Principles. Part 2: Overview of Process
Categories and Feedstock (ISO 17296-2:2016).*

IPG Photogenics Corporation *YLS-SM Ytterbium Single-Mode CW Systems. [Website]* [Cited 15.04.2022] Available at: https://www.ipgphotonics.com/en/products/lasers/high-power-cw-fiber-lasers/1-micron/yls-sm-1-10-kw.

Milewski JO (2017) *Additive Manufacturing of Metals from Fundamental Technology to Rocket Nozzles, Medical Implants, and Custom Jewelry.* Cham: Springer International Publishing.

Scopus. 2022 [Website] [Cited 15.04.2022] Available at: https://www.scopus.com.

Syed WUH, Li L (2005) Effects of wire feeding direction and location in multiple layer diode laser direct metal deposition. *Applied Surface Science* 248(1): 518-524.