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MONITORING DIRECTED ENERGY DEPOSITION PROCESSES IN ADDITIVE MANUFACTURING

DIRECTED ENERGY DEPOSITION -PROSESSIEN MONITOROINTI AINETTA LISÄÄVÄSSÄ VALMISTUKSESSA

Mikko Puoskari 12.1.2015
Työn tarkastaja: DI Tuomas Purtonen

ABSTRACT

Lappeenranta University of Technology
LUT School of Energy Systems
LUT Mechanical Engineering

Mikko Puoskari

Monitoring Directed Energy Deposition Processes in Additive Manufacturing

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The purpose of this study is to find out how laser based Directed Energy Deposition processes can benefit from different types of monitoring. DED is a type of additive manufacturing process, where parts are manufactured in layers by using metallic powder or metallic wire. DED processes can be used to manufacture parts that are not possible to manufacture with conventional manufacturing processes, when adding new geometries to existing parts or when wanting to minimize the scrap material that would result from machining the part. The aim of this study is to find out why laser based DED-processes are monitored, how they are monitored and what devices are used for monitoring. This study has been done in the form of a literature review.

During the manufacturing process, the DED-process is highly sensitive to different disturbances such as fluctuations in laser absorption, powder feed rate, temperature, humidity or the reflectivity of the melt pool. These fluctuations can cause fluctuations in the size of the melt pool or its temperature. The variations in the size of the melt pool have an effect on the thickness of individual layers, which have a direct impact on the final surface quality and dimensional accuracy of the parts. By collecting data from these fluctuations and adjusting the laser power in real-time, the size of the melt pool and its temperature can be kept within a specified range that leads to significant improvements in the manufacturing quality. The main areas of monitoring can be divided into the monitoring of the powder feed rate, the temperature of the melt pool, the height of the melt pool and the geometry of the melt pool. Monitoring the powder feed rate is important when depositing different material compositions. Monitoring the temperature of the melt pool can give information about the microstructure and mechanical properties of the part. Monitoring the height and the geometry of the melt pool is an important factor in achieving the desired dimensional accuracy of the part.

By combining multiple different monitoring devices, the amount of fluctuations that can be controlled will be increased. In addition, by combining additive manufacturing with machining, the benefits of both processes could be utilized.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
LUT School of Energy Systems
LUT Kone

Mikko Puoskari

Directed Energy Deposition –prosessien monitorointi ainetta lisäävässä valmistuksessa

Kandidaatintyö

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Työn tarkoituksena on tutkia, miten laserin käyttöön perustuvissa Directed Energy Deposition (DED) eli materiaalin ja lämmön kohdistus –prosesseissa voidaan hyödyntää monitorointia. DED on yksi ainetta lisäävistä valmistusmenetelmistä, jossa kappaleita valmistetaan kerroksittain käyttäen metallijauhetta tai -lankaa. DED-prosesseja voidaan soveltaa silloin, kun ei ole mahdollista valmistaa tuotetta perinteisillä valmistusmenetelmillä, kun halutaan lisätä uusia muotoja jo valmiisiin kappaleisiin tai kun halutaan vähentää hukkamateriaalin määrää, jota syntyisi, kun valmistettaisiin kappale koneistamalla. Työssä selvitetään miksi laserin käyttöön perustuvia DED-prosesseja monitoroidaan, miten niitä monitoroidaan ja mitä laitteita monitorointiin käytetään. Työ tehtiin kirjallisuustutkimuksena.

Valmistuksen aikana DED-prosessi on herkkä erilaisille muutoksille, kuten lasersäteen absorption muutoksille, jauheensyötön vaihteluille, lämpötilan vaihteluille, kosteudelle tai säteen heijastumiselle sulasta. Näistä vaihteluista voi aiheutua sulan koon vaihtelua tai sulan lämpötilan vaihtelua. Sulan koon vaihtelu vaikuttaa yksittäisen kerroksen korkeuteen, jolla on suora vaikutus valmistettavan kappaleen lopulliseen pinnanlaatuun ja mittatarkkuuteen. Keräämällä tietoa parametrien vaihteluista ja reaaliaikaisesti säätämällä esimerkiksi lasertehoa, voidaan sulan koko ja sulan lämpötila pitää haluttujen rajojen sisällä, jolloin valmistuksen laatua voidaan parantaa merkittävästi. Monitoroitavat alueet voidaan pääosin jakaa jauhesyötön, sulan lämpötilan, sulan korkeuden ja sulan geometrian monitorointiin. Jauhesyötön monitorointi on tärkeää, kun valmistetaan kappale eri seoksista. Sulan lämpötilan monitoroinnilla saadaan tietoa mikrorakenteesta ja mekaanisista ominaisuuksista. Sulan korkeuden ja geometrioiden monitorointi on tärkeää kappaleen lopullisen mittatarkkuuden saavuttamisen kannalta. Yhdistämällä useita eri monitorointilaitteita voidaan vaikuttaa mahdollisimman moneen valmistuksen aikana tapahtuvaan muutokseen samanaikaisesti. Lisäksi yhdistämällä ainetta lisäävän valmistuksen ja koneistamisen, voitaisiin hyödyntää molempien valmistusmenetelmien hyviä puolia.

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ABBREVIATIONS

ALM	Additive Laser Manufacturing
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CAD	Computer-Aided Design
CCD	Charge-Coupled Device
CMOS	Complementary Metal-Oxide Semiconductor
CMT	Cold Metal Transfer
CO2	Carbon Dioxide
DCEP	Direct Current Electrode Positive
DED	Directed Energy Deposition
DMD	Direct Metal Deposition
EB	Electron Beam
EBDM	Electron Beam Direct Manufacturing
EBFFF	Electron Beam Freeform Fabrication
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
LENS	Laser Engineered Net Shaping
LMD	Laser Metal Deposition
NASA	The National Aeronautics and Space Administration
Nd:YAG	Neodymium-Doped Yttrium Aluminum Garnet
RGB	Red Green Blue
SLR	Single-Lens Reflex
SMD	Shaped Metal Deposition
STL	Stereolithography
TIG	Tungsten Inert Gas
WAAM	Wire and Arc Additive Manufacturing

1 INTRODUCTION

Additive manufacturing (AM) is a manufacturing process where parts are manufactured by adding material in layers (Gibson, Rosen & Stucker, 2010, p. 2). Unlike traditional manufacturing methods such as machining where material is subtracted to get the desired shape, in AM only the required material can be added, complex 3-dimensional parts can be made and material can be saved (Gibson et al., 2010, p. 1). With recent advances in the technology, AM processes offer viable alternatives to conventional manufacturing methods such as milling or casting. AM processes can enable manufacturing parts with increased functionality and mechanical properties while also reducing the mass and costs related to manufacturing the parts. (Ponche et al., 2014, p. 389) According to Wohlers (2013, p. 178) AM processes can reduce the costs of: “tooling, manufacturing, inventory, assembly, labor, maintenance and inspection”. Due to the reduced need for assembly, designers can design a few complex parts instead of a large number of simple parts. This reduction in the amount of parts can lead to more simplified supply chain logistics and a reduction in lead times. (Wohlers, 2013, p. 178.) According to Ponche et al. (2014, p. 389) AM processes have broad applications in the die mould industry, the aviation industry and the aerospace industry. According to Wohlers (2013, p. 66), AM processes could also be used as an alternative way of manufacturing parts from Ti-6Al-4V due to the difficulties of eliminating porosity while casting.

1.1 Background

The basic concept of AM is to divide a 3-dimensional Computer-Aided Design (CAD) model into 2-dimensional layers and build the part one layer at a time layer-upon-layer. Originally the term rapid prototyping has been used to describe this type of manufacturing but as the output quality of these machines has increased and the properties of the manufactured products have started to match the desired properties of the final products, the term AM has become more appropriate. (Gibson et al., 2010, p. 1.) According to Wohlers (2013, p. 14), some other terms that have been used to describe AM are: “additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, freeform fabrication” and many others. Even though AM is the official standardized term in the industry, also the term 3D printing has become a popular term to describe this process. The American Society for Testing and Materials, ASTM F42 defines 3D printing as: “the fabrication of objects through the deposition of a material using a print head, nozzle, or other printer technology”. (Wohlers, 2013, p. 14.)

In 2012, according to Salmi (2013, p. 24) the ASTM divided AM processes into seven categories: “binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat polymerization”. These processes utilize either polymer materials or metallic materials as build materials. (Salmi, 2013, p. 24.) According to Wohlers (2013, p. 61) directed energy deposition (DED) is defined as a: “deposition process where focused thermal energy is used to fuse materials together by melting as the material is being deposited”. The source of the energy used in most cases is a laser and the deposit material is a metal powder (Wohlers, 2013, p. 61). DED processes differ from powder bed processes as instead of melting metal powder that is pre-laid on the build platform, in DED the deposit material melts as its being deposited (Gibson et al., 2010, p. 237).

Even though DED processes can be used to manufacture highly complex parts, one of the main concerns is that they are highly sensitive to disturbances caused by fluctuations in the process parameters. These fluctuations can cause significant changes in the quality of the process. (Toyserkani, Khajepour & Corbin, 2004, p. 149.) To overcome many of the issues, monitoring and closed loop control of the process is required. In closed loop control, the process is monitored by various devices and data from these devices is used as feedback to control the process parameters to maintain the desired process conditions. (Song et al., 2012, p. 248.)

1.2 Research problem, objectives and delimitation

The research problem of this study is to research how laser based DED processes can benefit from different types of monitoring. This study aims to find out why laser based DED processes are being monitored, how they are being monitored and what devices are used for monitoring. This study will first introduce the basic concept of additive manufacturing and DED processes. Secondly, ways to monitor laser based DED processes are presented. Presentation of the DED processes will be categorized by the type of energy source they use and the focus for the type of monitoring devices will be restricted to laser based DED processes.

1.3 Research methods

This study was done in the form of a literature review. At first the research was done on the basic concept of additive manufacturing and what types of processes are regarded as directed energy deposition (DED). Secondly, monitoring and the use of closed loop control were researched. Articles on additive manufacturing were mainly used, however in some cases articles on laser cladding were also studied due to the similarity of the processes. In addition, due to the limited number of published articles on the specific subject, conference papers, books and dissertations were also used as references.

2 MONITORING DIRECTED ENERGY DEPOSITION PROCESSES IN ADDITIVE MANUFACTURING

This chapter will first present the basics of additive manufacturing and directed energy deposition (DED) processes. Secondly, ways of monitoring and controlling laser based DED processes will be presented.

2.1 Additive manufacturing (AM)

The AM process starts off with a 3-dimensional CAD model of the part to be manufactured. The model can be made by hand with almost any professional CAD solid modeling software or by scanning an existing physical model with laser scanning equipment. After a 3-dimensional CAD model has been chosen, the data is converted into an STL-file. The STL-file, in short, is a file that contains directions for the AM machine. The STL-file describes the geometry of the 3-dimensional CAD model by using triangulation and forms the basis for calculating the slices for the AM machine. (Gibson et al., 2010, p. 4.) The converted STL-file is sliced into 2-dimensional layers of the desired layer thickness by the used software and transferred to the AM machine where final adjustments to the size, position and orientation for building are made. After this, the correct parameters needed for building are set, tool paths are created and the manufacturing process is started. Figure 1 shows a CAD model of a teacup and the general idea of slicing a model into 2-dimensional layers of two different thicknesses. (Gibson et al., 2010, p. 5.)

Figure 1. The general idea of slicing a CAD-model into 2-dimensional layers (Gibson et al., 2010, p. 2).

Depending on the AM process, manufacturing a part in AM is ideally an automated process for the most part. However as discussed previously, monitoring and using the monitoring data as feedback to control the process is especially important with DED processes. After the manufacturing process has reached completion, the finished part is removed from its building substrate, however in some cases the substrate can also be a part of the final part. Depending on the application of the part, the part is either ready for use or it is set up for post processing. (Gibson et al., 2010, p. 5.) Figure 2 shows the general process flow of manufacturing a teacup from creating a 3-dimensional CAD model to the finished part.

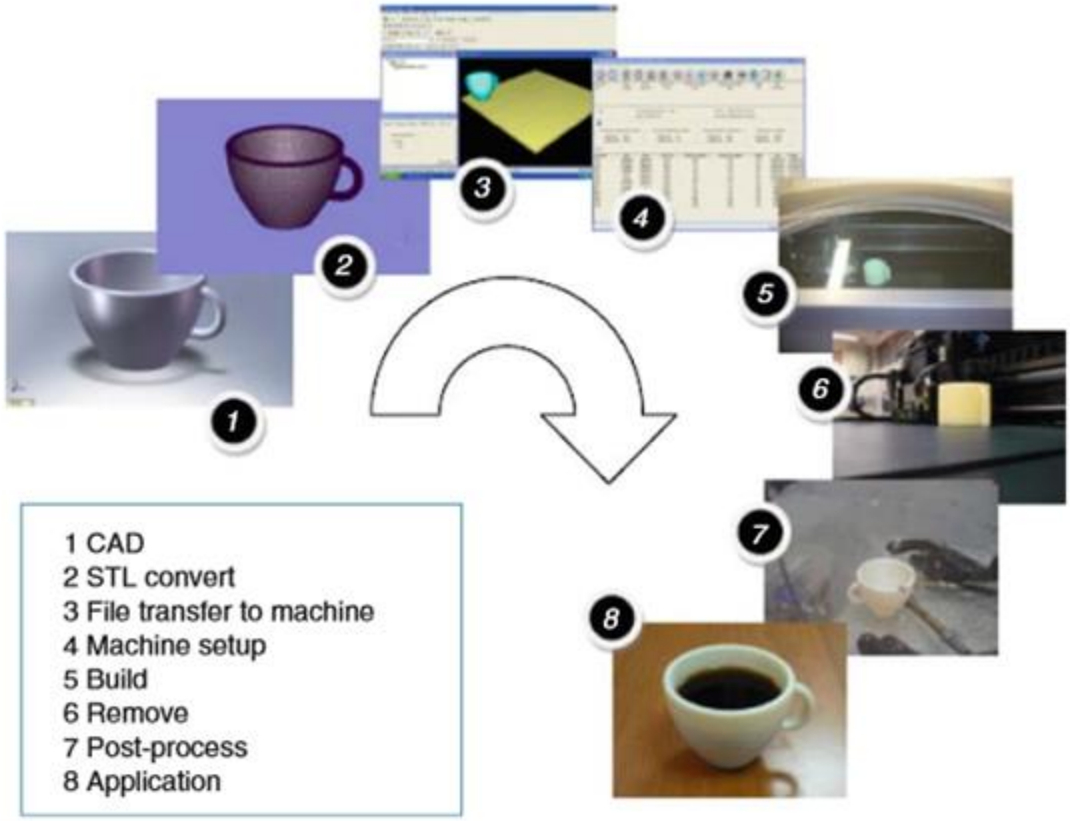


Figure 2. The general process flow for manufacturing with AM (Gibson et al., 2010, p. 4).

2.2 Directed energy deposition (DED) processes

According to Wohlers (2013, p. 61) directed energy deposition (DED) is defined as a: “deposition process where focused thermal energy is used to fuse materials together by melting as the material is being deposited”. The source of the energy used in most cases is a laser and the deposit material is a metal powder (Wohlers, 2013, p. 61). DED processes differ from powder bed processes in a way that instead of melting metal powder that is pre-laid on the build platform, in DED the deposit material melts as its being deposited (Gibson et al., 2010, p. 237).

In this literature review, in addition to laser, also the use of electron beam (EB), gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) are researched. In addition to metal powder, processes using metal wire are also presented.

2.3 Laser based DED processes

Laser based DED processes use laser as a heat source and metal powder as its deposit material. Terms that refer to laser based DED processes are laser engineered net shaping (LENS) (Mudge & Wald, 2007, p. 44), direct metal deposition (DMD) (Song et al., 2012, p. 247), additive laser manufacturing (ALM) (Ponche et al., 2014, p. 389), laser metal deposition (LMD) (Barua et al., 2014, p. 77) and many others. Although all of these processes use a laser as their energy source and metal powder as the deposit material, what differentiates the machines from each other, according to Gibson et al. (2010, p. 238), are properties such as: “laser power, laser spot size, laser type, powder delivery method, inert gas delivery method, feedback control scheme, and/or the type of motion control utilized. “ (Gibson et al., 2010, p. 238.)

2.3.1 Laser based DED machines

A typical laser based DED system consists of a high-powered laser (Santos et al., 2006, p. 1465), a powder feed unit, a multiple-axis computer-controlled positioning system and a glove box (Atwood et al., 1998, p. 5). The high-powered laser is focused onto the surface of the substrate which forms a molten pool that the metallic powder is then deposited and absorbed into. As the laser beam moves away, the molten pool turns solid and forms a layer on the substrate. The used substrate can be an already existing part where new geometry can be deposited or a flat plate where an entirely new part will be manufactured. (Gibson et al., 2010, p. 240.) A laser based DED system can be seen in figure 3.

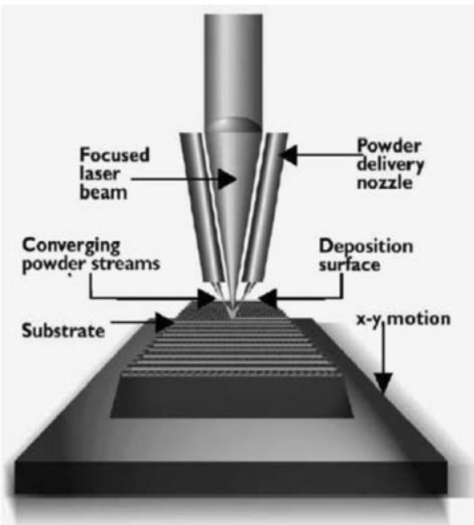


Figure 3. LENS Process (Bandyopadhyay et al., 2009, p. 31).

The powder can be delivered to the molten pool from an angle or coaxially with the laser beam. When a proper system design and a set-up are used, a well-designed coaxial nozzle can achieve and exceed an 80 % powder use efficiency. (Vilar, 1999, p. 71.) The powder can be delivered by using multiple nozzles by a gas jet. According to Gibson et al. (2010, p. 243): “The main benefit of a 4-nozzle feeding system is that the flow characteristics of 4-nozzle feeding gives more consistency in build height for complex and arbitrary 3D geometries that involve combinations of thick and thin regions.” However, when comparing multiple nozzles to a single nozzle, the overall powder utilization in a single nozzle system can be higher and it leads to a more simple design, which can lower the overall cost. (Gibson et al., 2010, p. 243.) Not being able to fully utilize the injected powder is an obvious disadvantage of laser based DED processes, however the unutilized powder can be collected and reused due to the process being done in an inert gas environment. Before the unutilized powder is used it has to be sifted, according to Vilar (1999, p. 64), sifting is done to remove: “unwanted contaminants and agglomerated powder particles.” (Vilar, 1999, p. 64.)

During the deposition process the substrate acts as a support and conducts heat away from the component (Zheng et al., 2008, p. 2228). A cold metallic substrate can trigger a rapid quenching effect, which can cause the deposited materials to cool at a very high rate. In a test done to measure this quenching effect, H13 tool steel was used as the deposit material, 304SS steel was used as the substrate material and argon as a shielding gas was used. The individual layer thickness was set to 0.25 mm and the width of the deposit was set to 0.40 mm. The results showed that the cooling rate can be up to 10^3 to 10^4 K/s, however as the amount of layers increases the rapid quenching effect decreases and even disappears. (Zheng et al., 2008, p. 2235.)

The substrate is moved by the computer-controlled positioning system in the XY-direction beneath the laser to create the geometry of the layer. After a layer is completed the focusing lens assembly and the powder delivery nozzles are moved in the positive Z-direction a distance equivalent to the thickness of one layer. The process is then repeated to complete the remaining layers. (Griffith et al., 1996, p. 126.) This process flow however is just one of the many possible variations that can be made available. The positioning system can also be made to tilt and rotate and the focusing lens assembly and the powder delivery nozzles can be attached into a multiple axis robot. Also in some machines only the deposition head is moved or only the substrate is moved (Optomec, 2014, p. 2.)

2.3.2 Types of lasers used in laser based DED systems

Typical lasers used for laser based DED systems are fiber lasers but also Nd:YAG and CO_2 lasers are used. The benefits of using fiber lasers and Nd:YAG lasers instead of CO_2 lasers are their higher absorptivity due to their operating wavelength and the ability for laser delivery through fiber optics. The higher absorptivity decreases the overall energy required for the deposition process which enables fiber lasers and Nd:YAG lasers to operate at approximately half the amount of power that a CO_2 laser would need to reach the same result. The ability to use fiber as a laser delivery system instead of a mirror delivery system with Nd:YAG and fiber lasers also increases the mobility of the focusing lens assembly and the powder delivery system which increases the amount of potential applications. (Mudge et al., 2007, p. 45.)

2.4 EB-based DED processes

Electron beam freeform fabrication, EBFFF, is a DED process that uses an electron beam as an energy source and metal wire as the deposit material. It was developed by NASA Langley, USA to be used in aerospace applications for fabricating complex parts and repair purposes. (Gibson et al., 2010, p. 247.) EBFFF can also be used to add detail to casted parts (Taminger & Hafley, 2003, p. 2). Another similar process is electron beam direct manufacturing (EBDM) from Sciaky, Inc. (Wohlers, 2013, p. 106).

2.4.1 Applications and process

The main reasons why EBFFF is considered as a great candidate for space-based applications is that it has better electrical efficiency compared to most lasers, it has the ability to work effectively in a vacuum where inert gases are not present and since it uses wire as the deposit material, it can be used in low gravity environments (Gibson et al., 2010, p. 247). In EBFFF a focused EB creates a molten pool on a substrate into which a wire feeder injects metal wire. EBFFF can be used effectively with any electrically conductive material. (Taminger & Hafley, 2006, p. 3.) The reason a wire is used instead of a powder is because of the difficulty of feeding powder in a vacuum environment since the gas that would be used to deliver the powder would be ionized in the EB (Taminger et al., 2003, p. 3). Another reason for using wire instead of powder is that the deposited parts may have lower porosity and less interference from natural oxide that is present on the surface of powder materials (Wanjara, Brochu & Jahazi, 2007, p. 2278). For EBFFF the wire utilization is nearly 100 %. The deposition rates can be as high as 2500 cm^3 per hour (Taminger et al., 2006, p. 3-4). Sciaky, Inc. has reported deposition rates that range from 3.2 to 9.1 kg of metal per hour. The downside of the high deposition rate however is that deposited parts have rough surfaces that require extensive finish machining. (Wohlers, 2013, p. 106.) The diameter of the deposited wire determines the smallest attainable detail that the EBFFF process can manufacture. Generally when adding fine details a fine diameter wire is used and larger diameter wires are used when manufacturing larger parts to increase deposition rates. The same equipment can be used to deposit thin and thick wire. (Taminger et al., 2006, p. 3-4.) An example of an EBFFF system can be seen in Figure 4.

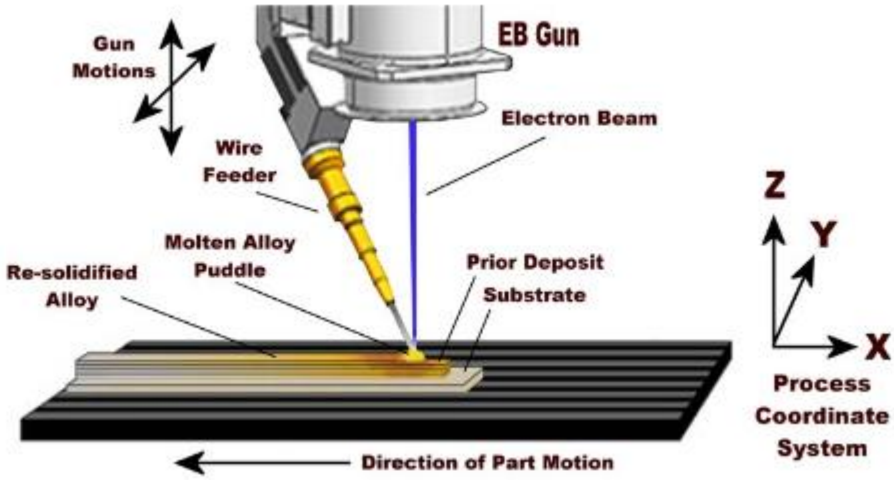


Figure 4. EBFFF process (Stecker et al., 2006, p. 36).

2.4.2 EBFFF systems

The basic components for an EBFFF machine are an EB gun, a vacuum system, a wire feeder and a positioning system. An example of an EBFFF system that is located in NASA Langley Research Center has a 42kW, 60kV accelerating voltage EB gun, a vacuum system, a positioning system and a dual wire feeder system that is capable of operating both independently and simultaneously. The dual wire feeder system can be used to deposit two different alloys or it can be equipped with thin and thick wire to switch for different sections of the part during the manufacturing. The positioning system in this system operates in 6-axis. The EB gun can be moved in X-, Y-, and Z-directions and it can be tilted. The positioning table can also be tilted and rotated. The system operates in a vacuum chamber of the size 2.5 m x 2 m x 2.7 m and requires a vacuum of $5*10^{-5}$ torr. (Taminger et al., 2006, p. 4.) NASA Langley Research Center also has a smaller EBFFF system. The system is made to be portable and it has successfully been used in flight on an aircraft. The vacuum chamber size in this system is 1m x 1m x 1m and it is capable of manufacturing parts 30 cm x 30 cm x 15 cm in size. This system uses a fixed low power EB gun, a single wire feeder and it has a 4-axis table positioning system which is capable of moving in the X-,Y- and Z-directions and capable of rotation. (Taminger et al., 2006, p. 3-4)

For the EB to work, the deposition takes place in a vacuum environment typically in the range of $1*10^{-4}$ to $1*10^{-5}$ Torr (Stecker et al., 2006, p. 35). The vacuum environment also has the benefit of having a clean processing environment which helps isolate the process from additional impurities that could end up in the final products (Tomus et al., 2010, p. 151) and therefore eliminates the need for shield gas (Taminger et al., 2006, p. 2). Avoiding these impurities is especially important in aerospace quality parts (Tomus et al., 2010, p. 151).

EB has a few advantages over using lasers. For lasers operating at room temperature the reflectance for metals can range from 40 % to 95 %, which results in a portion of the energy from the weld pool to be reflected out and lost to the atmosphere. This is a problem when depositing reflective materials such as aluminum (Stecker et al., 2006, p. 36.) and copper (Taminger et al., 2003, p. 2). Another advantage, especially when comparing EB to CO_2 lasers is the power efficiency, which can be 90 % or better. Lastly because the EB operates in a high vacuum oxygen-free atmosphere, a secondary inert gas is not needed to shield the process. (Stecker et al., 2006, p. 36.)

The EBFFF manufactures parts in the same layer-wise way as other AM processes from CAD data. The part is deposited into a near-net shape part and typically once the deposition is complete the part is finished by machining. (Taminger et al., 2006, p. 4.)

2.5 Arc welding based DED processes

Shaped metal deposition (SMD) is a DED process patented by Rolls Royce and licensed to the University of Sheffield (Escobar-Palafox, Gault & Ridgway, 2011, p. 622). As a manufacturing concept, using wire and an arc for AM dates back to the 1970s in West Germany where submerged arc welding was used for large scale metal component manufacturing (Kazanas et al., 2012, p. 1043). Another term used to describe arc welding based DED is wire and arc additive manufacturing (WAAM) (Kazanas, 2012, p. 1042).

2.5.1 Processes and applications

Two of the main advantages of using arc welding processes for AM purposes are their ability to reach high deposition rates compared to other AM processes and high wire utilization efficiencies which can go up to 100 % (Almeida & Williams, 2010, p. 25). While the accuracy and the surface finish of the deposited product is lower compared to laser or EB processes (Baufeld, Biest & Gault, 2010, p. 106) the increased efficiency reduces the amount of scrap metal produced when comparing to traditional machining methods. The use of SMD has especially been investigated for manufacturing parts with the material Ti-6Al-4V (Escobar-Palafox et al., 2011, p. 623). According to Escobar-Palafox (2011, p. 623) 60 % of titanium production is Ti-6Al-4V and it is widely used in aerospace, medical, sport car and maritime industries. The difficulties of shaping titanium alloys by using traditional methods such as casting, machining and forging as well as the high costs of scrap material caused by machining, have led to the investigation of using SMD. (Baufeld et al., 2011, p. 1) According to Kazanas (2012, p. 1043), when manufacturing aircraft parts in the aerospace industry by traditional manufacturing processes, in some cases, the buy-to-fly ratio, which is the ratio of bought material that ends up going to the aircraft, can even be as high as 10:1. Deposited parts using SMD with the material Ti-6Al-4V can be seen in figure 5.

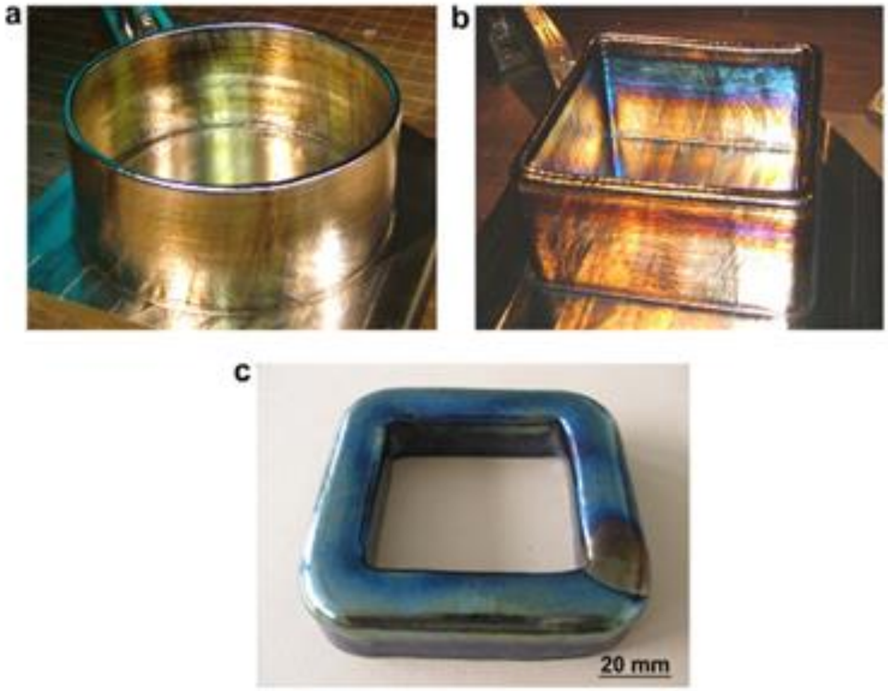


Figure 5. Deposited parts using SMD with the material Ti-6Al-4V (Baufeld et al., 2010, p. 108).

As with the previously discussed AM processes, SMD also makes manufacturing parts directly from 3-dimensional CAD models possible by using CAD software to design the part and software to create necessary welding paths for the manufacturing process (Baufeld, Biest & Gault, 2009, p. 1536). Compared to traditional methods such as forging or machining, where components are built by subtracting material from the work piece, in SMD the material is added to get the desired shape. When comparing SMD to alternative manufacturing methods the main benefits become apparent. According to Escobar-Palafox et al. (2011, p. 622), the three ways to manufacture a part are by machining a part from a solid block, forging or casting the part to a nearer net shape so less material needs to be machined or by using a powder based AM process. In the first method a large amount of raw material, coolant and energy is wasted. In the second method less coolant and less machining are needed, however large amounts of energy for the forging or casting are required. Additionally when using forging or casting there are high costs and time is consumed if modifications to moulds and dies are done. Therefore forging or casting to a nearer net shape way of manufacturing is not very flexible. The third manufacturing method is good for manufacturing small detailed parts, however manufacturing large parts with this method is often slow and may not even be possible. (Escobar-Palafox et al., 2011, p. 622.)

The two main welding processes that can be used are GTAW and GMAW. An arc welding based DED system set-up, GTAW for example, can consist of a TIG welding torch that is attached to a 6-axis Kuka robot and a 2-axis table. The welding wire is fed into a controlled atmosphere chamber by a motorized roller guide that ensures the wire deposition rate remains constant. (Baufeld et al., 2010, p. 106.) Additional equipment that can be used are an oxygen monitor to measure and maintain the appropriate atmosphere, a weld monitor to log the current, voltage and wire speed throughout the process, pyrometers to monitor the temperature of the weld, multiple thermocouples and a thermal camera (Escobar-Palafox et al., 2011, p. 624).

2.5.2 Cold metal transfer

One significant benefit of using GTAW over GMAW is that it is free of spattering (Wang & Kovacevic, 2001, p. 1520). Although spatter free, the deposition rates of GTAW-based DED processes are about 1 kg per hour, which are lower compared to the GMAW-based DED processes, which can reach deposition rates of several kilograms per hour. The drawback for (DCEP)-GMAW-based DED processes when welding titanium alloys however is its poor welding conditions. The poor welding conditions can lead to an unstable, uncontrollable, arc wandering and high spattering process which reduces the overall process efficiency. (Almeida et al., 2010, p. 26.)

Many of the poor conditions that occur during the GMAW-based DED process can however be overcome by combining GMAW with a welding method called cold metal transfer (CMT) (Kazanas et al., 2012, p. 1043). CMT is a welding method that uses digital process-control to retract the welding wire when detecting a short circuit. Retracting the wire helps to detach the droplet from the wire. The wire motion is then reversed and the process is repeated. The basic idea of CMT can be viewed in Figure 6. The main benefits of using CMT are that it has reduced thermal input, it is spatter-free and it has a stable arc. (Fronius, 2014, p. 3.)

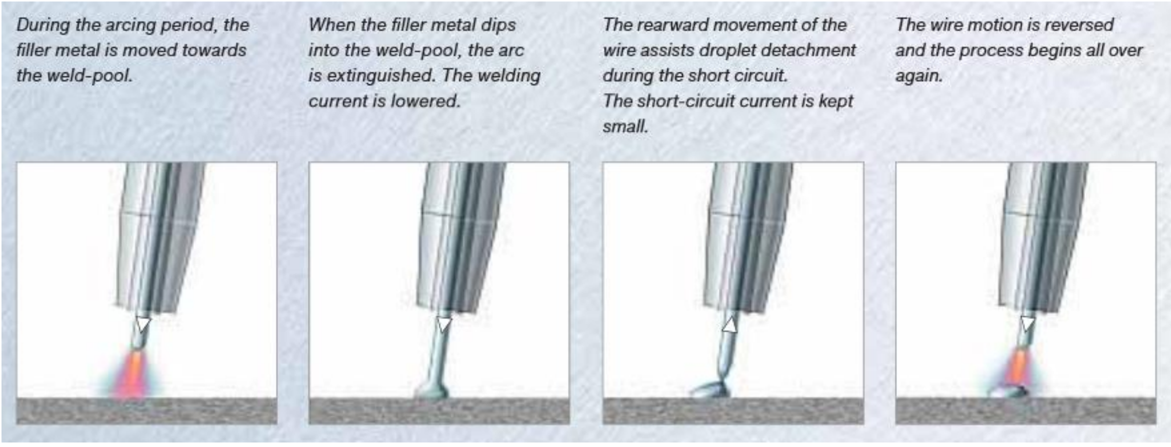


Figure 6. Cold metal transfer (CMT) (Fronius, 2014, p. 3).

With other AM processes, one of the key problems is manufacturing constructions with overhangs or inclined structure walls that have angles less than 45 degrees without the use of support structures. Kazanas et al. (2012, p. 1044) combined GMAW with CMT and managed to build inclined walls with angles of 60, 45, 30 and 15 degrees without using support structures and without tilting the substrate. The walls were 200 mm long with wall thicknesses ranging between 4 mm to 5 mm. The tests were done using a carbon steel S355 substrate of the size 350 mm x 300 mm x 15 mm, a shielding gas mixture of 80 % argon and 20 % CO_2, a ER70S-6 grade 0.8 mm diameter welding wire, Fronius CMT, Transpulse Synergic 5000 welding machine and an ABB type MTB 250 6-axis robot. (Kazanas et al., 2012, p. 1044.) The wall angle experiments can be seen in Figure 7. The group also conducted tests of a 50 mm square section (Kazanas et al., 2012, p. 1047), a 200 mm 0 degree horizontal overhang (Kazanas et al., 2012, p. 1048) and 50 mm radius semicircle as shown in Figure 8 (Kazanas et al., 2012, p. 1049).

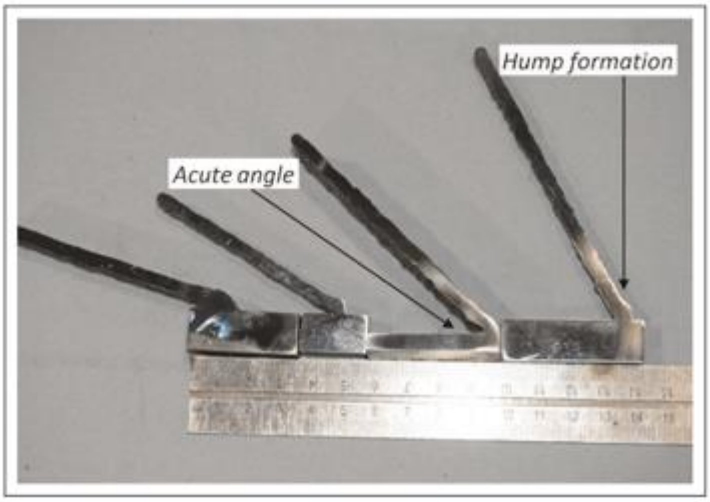


Figure 7. Wall angle experiments. (Kazanas et al., 2012, p. 1045).

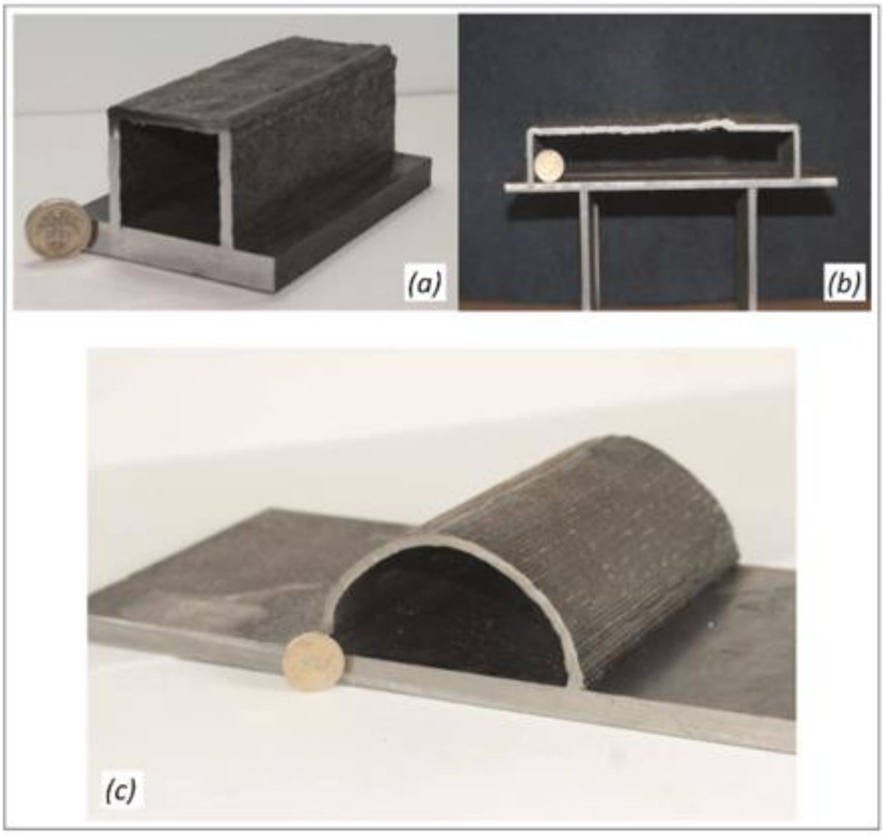


Figure 8. (a) 50 mm square section (b) 200mm 0 degree horizontal overhang (c) 50 mm radius semicircle (Kazanas et al., 2012. p. 1049).

2.6 Monitoring DED processes

DED processes can be used to manufacture highly complex parts, however one of the main concerns is that they are highly sensitive to disturbances caused by fluctuations in the process parameters. Fluctuations in the process parameters can cause significant changes in the quality of the process. (Toyserkani et al., 2004, p. 149.) For example, an increase or decrease in laser power can affect the size of the molten pool or, according to Toyserkani et al. (2004, p. 149) fluctuations in the powder flow rate can cause significant changes in the “overall geometry and microstructure” of the deposit. (Toyserkani et al., 2004, p. 149.) Other factors that can cause the process to deviate are environmental factors such as ambient temperature, humidity and factors in the process itself such as surface tension, absorptivity dependent on temperature and reflectivity of the melt pool (Song et al., 2012, p. 248). These fluctuations in the process can cause defects such as porosity, bad bonding, over-building and under-building which affect the geometrical accuracy of the part (Song et al., 2012, p. 248). Since the AM process is a layer-by-layer manufacturing process, keeping the layer thickness at a constant thickness is critical for the overall quality of the part. A deposition error such as a variation in deposition height in an individual layer has a direct impact on the following layers. If the variation in deposition height is too high or too low, face milling might be needed to continue the manufacturing of the part. Additional manufacturing operations can however distort the part and increase the manufacturing time. (Ponche et al., 2014, p. 393.)

2.6.1 Open loop control and closed loop control

The main parameters that affect the deposition quality can be divided into two groups. The first group is intrinsic parameters and the second group is extrinsic parameters. The intrinsic parameter group includes the parameters that are related to the properties of the substrate and the metallic powder such as absorptivity, thermal conductivity, heat capacity, thermal diffusivity and the geometry of the work piece. (Toyserkani et al., 2004, p. 149.) According to Toyserkani et al. (2004, p. 149) the extrinsic parameters are parameters related to the used hardware such as: “the laser, the powder feeder and the positioning system”.

Controlling the intrinsic parameters cannot always be done directly, however the changes in these parameters can be studied and that is where the role of monitoring comes in.

Monitoring the intrinsic parameters gives valuable data of the process, which can then be modified by adjusting the extrinsic parameters. Controlling the extrinsic parameters can be used to compensate for the changes that occur in the intrinsic parameters. (Toyserkani et al., 2004, p. 149.)

2.6.2 An open loop DED system

DED processes are conducted by either having an open or a closed loop control system. In an open loop process, according to Toyserkani et al. (2004, p. 149) parameters such as: “laser average power, focal point, speed, and powder feed rate”, are given preset values that remain the same throughout the process. Parameter values that result in achieving a good quality for the process are found through trial and error. Problems with an open loop process however are that laser based DED processes are highly sensitive to internal and external disturbances and variations in intrinsic and extrinsic parameters can affect the overall quality of the manufactured part significantly. For example, fluctuations in the absorbed laser power can significantly change the geometry (Toyserkani et al., 2004, p. 149.) and the temperature (Song et al., 2012, p. 248) of the melt pool and variations in the powder flow rate, according to Toyserkani et al. (2004, p. 149), can cause changes in the: “overall geometry and microstructure of the part”. As the amount layers increases, the heat transfer dynamics also change due to the rapid cooling effect caused by the substrate. The effect is mainly relevant for the first few layers until the part reaches a critical amount of layers where the substrate no longer has effect on the process. (Sammons, Bristow & Landers, 2013, p. 4.) This indicates however that when manufacturing multiple layered parts where the parameter values are kept the same, the end result can differ significantly from the expected result (Sammons et al., 2013, p. 1). In addition, with an open loop process finding the right set of parameters can be very time consuming, however when the correct parameters are found and the application stays the same, an open loop system can be a cost effective solution (Toyserkani et al., 2004, p. 150).

2.6.3 Closed loop DED system

In a closed loop control system, according to Iravani-Tabrizipour (2007, p. 344) parameters such as: “melt pool temperature, melt pool size and rate of solidification”, can be monitored and the monitoring data, according to Toyserkani & Khajepour (2006, p. 632), can: “be used as a feedback signal” to control the process by modifying the controllable parameters. For example, variations in the height of the melt pool can be compensated by adjusting the laser power online to keep the height of the melt pool within a desired range (Song et al., 2012, p. 248). Although the open loop control system can be a cost effective solution, when manufacturing complex 3-dimensional parts, controlling the process parameters could be critical to achieving the manufacturing of high quality products (Ponche et al., 2014, p. 389). The monitoring devices used in laser based DED processes will be presented in the following chapters.

2.7 Monitoring the powder feed rate

Different ways of monitoring the powder feed rate are by monitoring the weight of the remaining powder inside the hopper, by utilizing a photodiode and a diode laser or by using a CCD (Charge-Coupled Device) camera to capture images from the powder stream. Monitoring the powder feed rate of the powder feeders is especially important when producing functionally graded materials or alloys. (Hu & Kovacevic, 2003, p. 51-52.) As previously mentioned, fluctuations in the powder flow rate can cause, according to Toyserkani et al. (2004, p. 149), significant changes in the: “overall geometry and microstructure” of the deposit (Toyserkani et al., 2004, p. 149).

2.7.1 Monitoring the powder feed rate by weight change

According to Toyserkani et al. (2004, p. 68), powder feeders can be categorized into: “gravity-based, mechanical wheel, fluidized-bed and vibrating” types of powder feeders. Of these power feeders, the monitoring and controlling of gravity-based, mechanical wheel based and fluidized-bed based powder feeders are further introduced.

2.7.2 Gravity based powder feeders

One type of gravity based powder feeder is a rotating disk based feeder. In these types of powder feeders the powder material is placed inside a powder container from where by the help of gravity, the powder material flows, according to Toyserkani et al. (2004, p. 69): “into a slot on a rotating disk”. The disk transfers the powder from the slot by rotating itself into a suction unit from where the powder is, according to Schneider (1998, p. 31): “transported to a powder nozzle by a gas stream.” The volumetric powder feed rate with this method is, according to Schneider (1998, p. 31): “controlled by the dimensions of the slot and the speed of the disk.” (Schneider, 1998, p. 31.) A gravity based powder feeder can be seen in Figure 9.

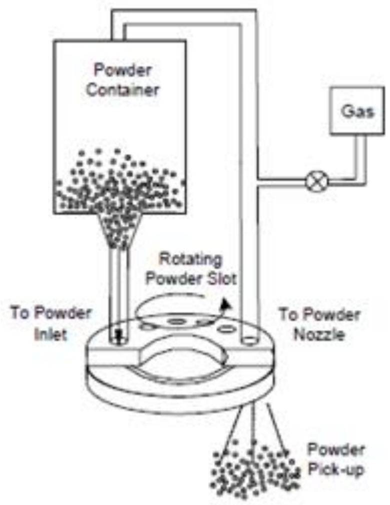


Figure 9. A gravity based powder feeder utilizing a rotating disk (Toyserkani et al., 2004, p. 70).

2.7.3 Mechanical wheel based powder feeders

A mechanical wheel based type of powder feeder is a powder feeder that utilizes a helical screw to feed the powder. With these types of powder feeders the powder is stored in the powder container from where it is transferred to a powder pick up and then transferred to the powder nozzle. (Schneider 1998, p. 31.) A way of monitoring the powder feed rate is to, according to Hu, Mei & Kovacevic (2002, p. 1254): “equip the device with an electronic weight scale to measure the weight of the metal powder inside the hopper.” According to Hu et al. (2002, p. 1254), the data collected from the weight changes in the hopper, is used as: “feedback to control the powder delivery rate”, by adjusting the rotational speed of the feed screw. Problems with this method of monitoring the powder feed rate is that the delivery has to be averaged over a relatively long period of time until a stable rotational speed of the feed screw is reached due to the low sampling frequency of the used feedback. (Hu et al., 2002, p. 1254.) According to Tang, Ruan, Landers & Liou, (2007, p. 23): “this technique is not adequate for on-line powder flow rate control due to the inherent low sampling frequency (e.g., 10 Hz).” A mechanical wheel based powder feeder can be seen in Figure 10.

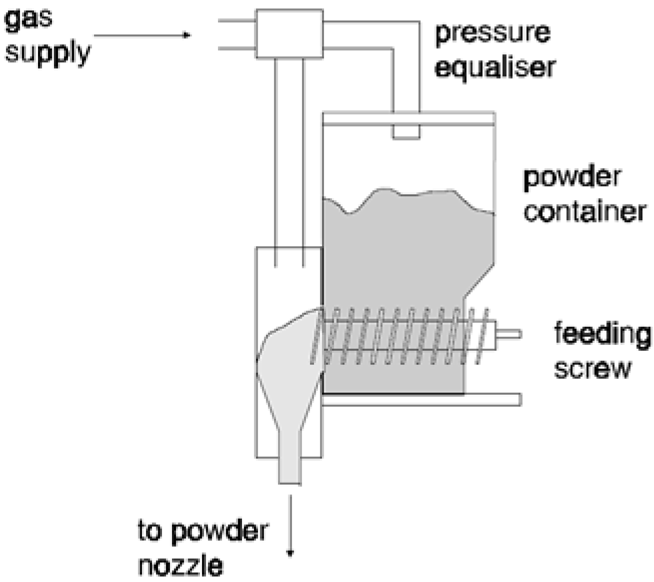


Figure 10. A mechanical wheel based powder feeder (Schneider, 1998, p. 32).

2.7.4 Fluidized-bed based powder feeder

The name of the fluidized-bed feeders comes from its use of the principles of fluid mechanics for the transportation of the metallic powder. A schematic diagram can be seen in Figure 11. In a fluidized-bed feeder, a high-pressure gas is used to fluidize the metallic particles by separating the particles from each other and to transfer them over a separating wall into a tube. From the tube the metallic powder is transported to the nozzle output by a carrier gas. (Koebler, 2010, p. 180.) A fluidized-bed feeder can provide stable and accurate powder feeding rates with feeding rates as low as 0.07 g/s. The change in weight of the powder is used to monitor the powder flow rate in these powder feeders. The flow rate is adjusted by adjusting the gas pressures between the hopper and the pickup shaft. (Hu, Chen & Mukherjee, 1998, p. 1288.)

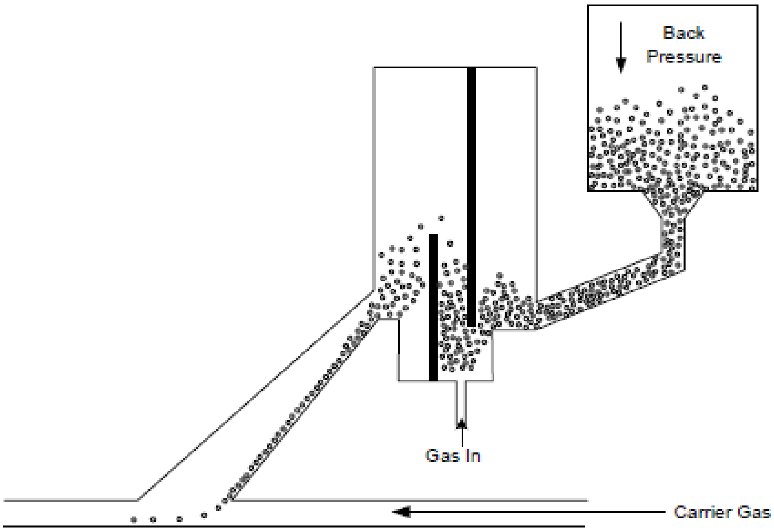


Figure 11. A fluidized-bed based powder feeder (Toyserkani et al., 2004, p. 73).

2.7.5 Powder feed rate monitoring by an optoelectronic sensor

The powder feed rate can also be monitored by monitoring the flowing powder itself. For this purpose a method was developed which, according to Hu & Kovacevic (2003, p. 53) utilizes: “a laser diode, a photodiode, and a glass window.” A basic demonstration of monitoring the powder feed rate with an optoelectronic sensor can be seen in Figure 12.

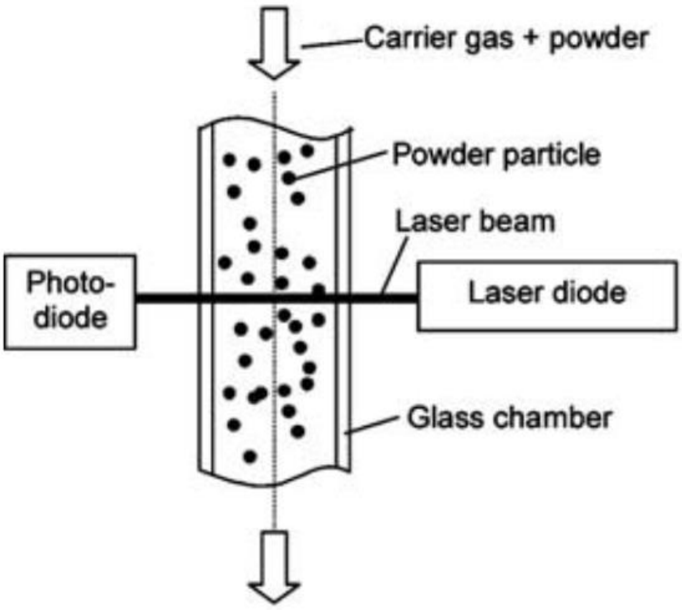


Figure 12. Powder feed rate monitoring by an optoelectronic sensor (Hu et al., 2002, p. 1255).

In this method of monitoring the beam of the diode laser passes through a uniform mix of metallic powder and carrier gas that flows inside a glass chamber and is received by a photodiode on the other side of the glass chamber. The powder delivery rate is measured by the amount of laser energy that the photodiode receives. The laser beam diffuses, absorbs and reflects from the powder particles and the amount of laser energy that passes through the powder stream is received by the photodiode. A decrease in the amount of laser energy received by the photodiode means an increased powder flow rate and vice versa. (Hu et al., 2003, p. 53.) The received energy is converted into a voltage signal. Figure 13 shows good linearity when comparing different measured averaged sensor output voltage signals at different powder delivery rates. (Hu et al., 2003, p. 53.)

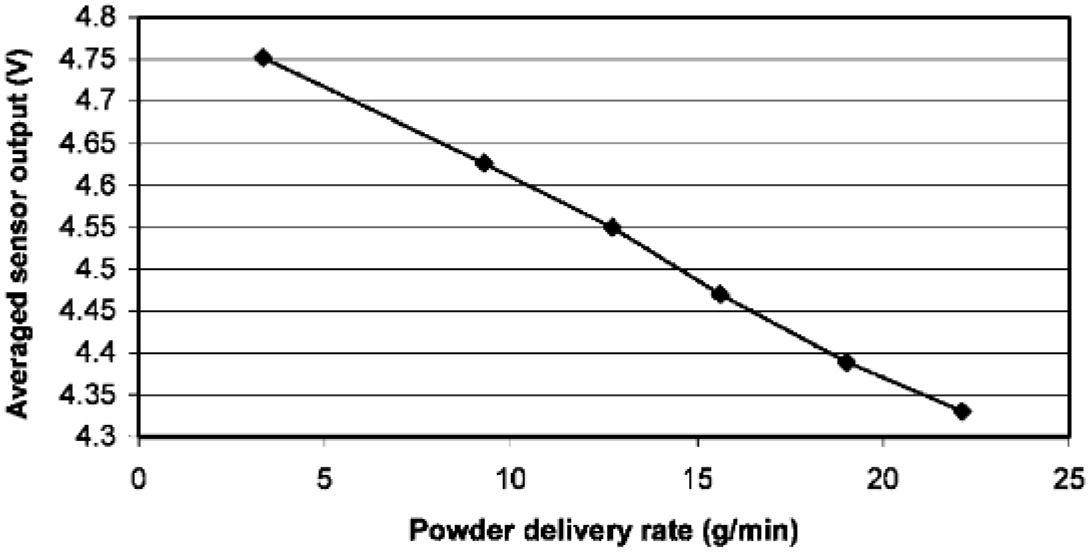


Figure 13. Powder delivery rate (g/min) in relation to averaged sensor output (V) (Hu et al., 2002, p. 1256).

The laser diode uses a power of less than 500 mW and operates at a wavelength of 600-710 nm. Data from the powder flow rate is obtained at the frequency of 10Hz. With this method powder rates in the range of 3 to 22 g/min can be measured, however many applications utilize powder feed rates of less than 3 g/min. (Hu et al., 2003, p. 53.) Another problem with this setup is that it cannot be used for in-process monitoring since it cannot withstand the high temperatures of the process near the deposition nozzle (Tang et al., 2007, p. 24).

2.7.6 Image based powder feed rate monitoring

The powder flow rate can also be monitored by using CCD cameras. The CCD camera is used to captures images continuously from the powder stream to detect the velocity of the powder particles, which can be seen in Figure 14. A significant benefit of using image based monitoring is that it is non-intrusive to the process. (Pinkerton & Li, 2004, p. 35.) By monitoring the powder particle velocities, the proper carrier gas flow rate can be selected and optimization of the conditions when depositing multifunctional multi-material deposits with materials of different properties such as size, density or shape can be done. (Smurov, Doubenskaia & Zaitsev, 2013, p. 115.) In addition to particle-in-flight monitoring, CCD-cameras can also be used to visualize the distribution of the particles in-flight online and particle jet stability control (Smurov et al., 2013, p. 120).

A special type of software package is used to process the tracks of the particles from the captured images by using statistical analysis (Doubenskaia, Bertrand & Smurov, 2004, p. 479). Figure 14 shows tracks of the particles-in-flight that have been stored by the software. The software marks each of the tracks with a beginning point, an ending point and then calculates the lengths of the tracks to retrieve the velocities of the individual particles. (Smurov et al., 2012, p. 1360-1361.) Liu et al. (2013, p. 105) found that increasing the gas flow rate causes an increase in the particle-in-flight velocity, however increasing the powder feed rate decreases the particle-in-flight velocity. The higher the particle size and the higher the density are, also decreases the particle-in-flight velocity (Liu et al., 2013, p. 105).

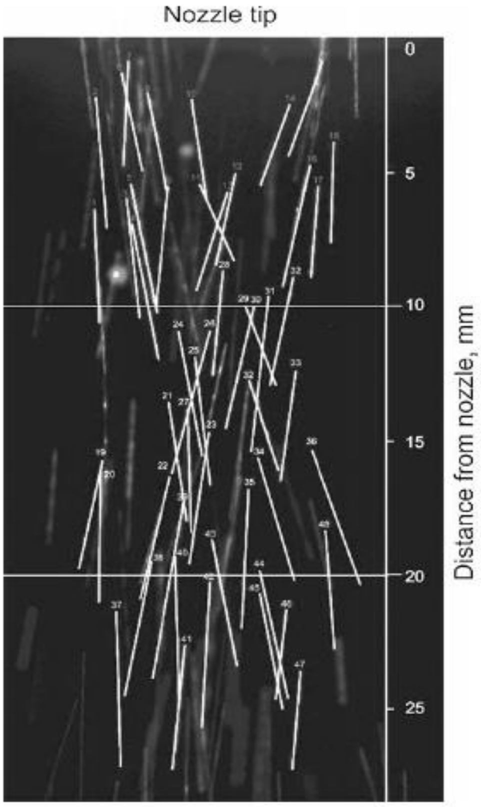


Figure 14. Tracks of particles-in-flight (Smurov et al., 2012, p. 1360).

Smurov et al. (2013, p. 116) also investigated the relation of gas flow rate to in-flight-particle velocity. Smurov et al. (2013, p. 116) found that a decrease of 18 l/min to 10 l/min in the gas flow rate resulted in a decrease of 20 % in the velocity of the particles, however when the decrease of 18 l/min to 10 l/min in the gas flow rate was done, the velocity of the particles increased by only 10 %. In other words by controlling the gas flow rate, the particle velocity can be controlled, however there exists a critical value after which increasing the gas flow rate has a limited effect. (Smurov et al., 2013, p. 116.) The dependence of particle velocity on the carrier gas flow rate and the distance from the nozzle can be seen in Figure 15.

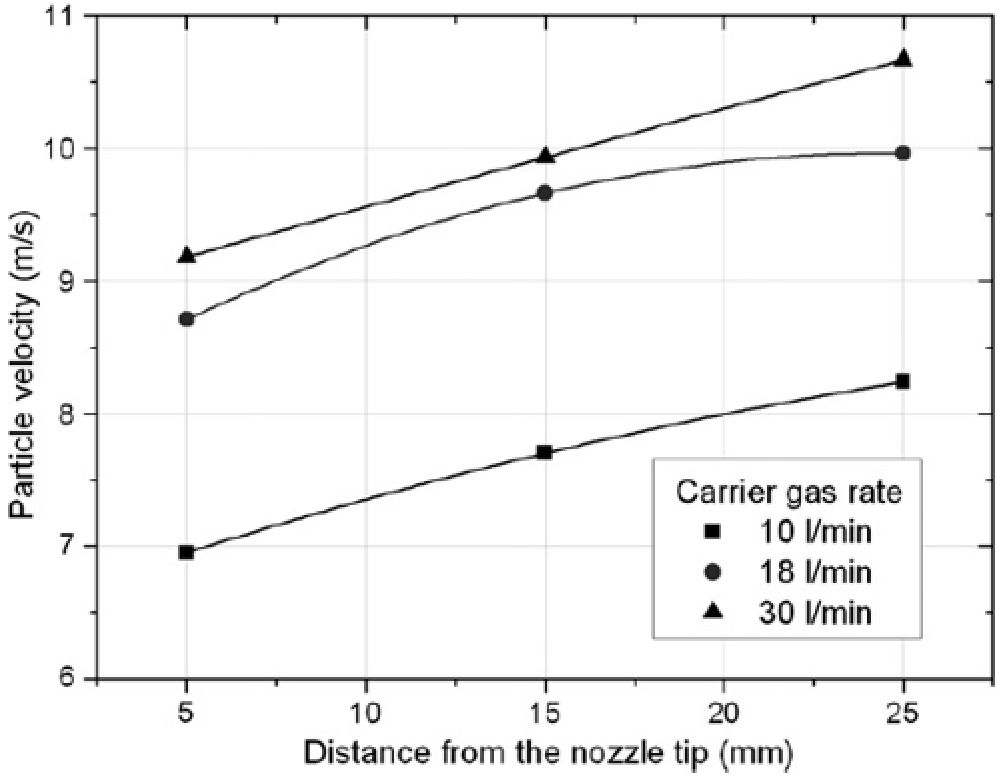


Figure 15. Dependence of particle velocity (m/s) on the carrier gas flow rate (l/min) and distance from the nozzle (mm) (Smurov et al., 2012, p. 1361).

2.8 Monitoring the temperature of the melt pool

According to Iravani-Tabrizipour (2007, p. 18), monitoring the temperature of the melt pool in deposition processes can give valuable information such as: “quality, dilution, microstructure properties, mechanical properties, mass flow and energy absorption”. According to Smurov (2007, p. 5), by controlling the temperature of the process, overheating and defects such as crack formation and residual porosity can be reduced. To monitor the temperature of the melt pool, a non-intrusive sensor is most preferable (Song et al., 2012, p. 248). Typical devices that have been used to monitor the temperatures are radiation pyrometers (Toyserkani et al., 2004, p. 152), acoustic pyrometers (Toyserkani et al., 2004, p. 153), ultrasonic pyrometers (Toyserkani et al., 2004, p. 153), photodiodes (Song et al., 2012, p. 248) and CMOS cameras (Barua et al., 2014, p. 81).

2.8.1 Radiation pyrometers

Radiation pyrometers have been used by Doubenskaia, Bertrand and Smurov (2004, p. 478) to monitor the temperature of the melt pool during the deposition process. Pyrometers utilize the fact that all objects emit electromagnetic radiation as a function of their temperature above absolute zero. Radiation pyrometers are used to measure this radiation at a known wavelength and to calculate the temperature of the object based on the measurements. (Morris & Langari, 2012, p. 366.) According to Morris et al. (2012, p. 372): "the emitted radiation-temperature relationship for a body depends on its emissivity". The calculation of the emissivity for a body can be very difficult and the calibration of the pyrometers has to be done for the particular body that will be measured (Morris et al., 2012, p. 372). Measuring the radiation at one known wavelength is called a single color pyrometer (Verhoeven, 2007, p. 206). Song et al. (2012, p. 249) have utilized a dual color pyrometer instead of a single color pyrometer in their setups. Two-color pyrometers have the benefit of being able to function in environments with fumes or dust, however they are not as accurate as other types of pyrometers (Morris et al., 2012, p. 372). In two-color pyrometers the radiation from the body is measured at two wavelengths. Detectors then produce output voltages from these two wavelengths. According to Morris et al. (2012, p. 372), the ratio of the output voltages is a function of the body's temperature. Therefore by measuring the body's radiation at two different wavelengths and calculating the ratio of the output voltages produced by the detectors, an object's temperature can be retrieved without separately calculating the body's emissivity. This setup is based on the assumption that the two measured wavelengths are very close to each other and therefore the emissivity is equal in these two wavelengths. This however is the cause of the inaccuracies in the measurements. (Morris et al., 2012, p. 372.)

2.8.2 Acoustic and ultrasonic pyrometers

The temperature can also be monitored by utilizing acoustic and ultrasonic pyrometers. These types of pyrometers utilize the fact that the flight time of sound is a function of temperature. By measuring the flight time of sound in the process zone, a temperature of the process zone can be retrieved. According to Toyserkani et al. (2004, p. 153), disadvantages of using acoustic pyrometers are their low sensitivity and noise rejection.

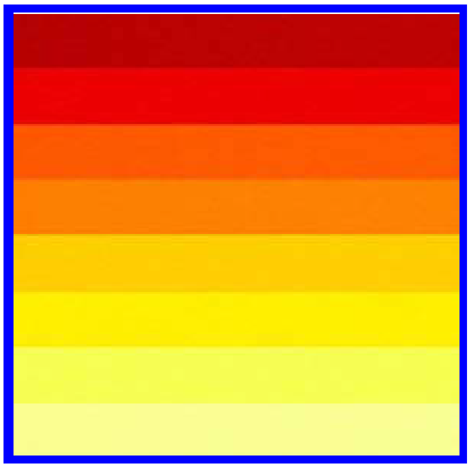
2.8.3 CMOS

CMOS (Complementary metal oxide semiconductor) cameras can also be used to monitor the temperature of the DED process. As previously discussed, during the DED processes, when rapid cooling occurs, heat from the molten pool rapidly flows to the substrate.

According to Barua et al. (2014, p. 80), Yang, Tian, Abidin & Wilson in their study: “Simulation of Edge Cracks Using Pulsed Eddy Current Stimulated Thermography” found that: “During heat transfer across a metallic substrate, heat flow is interrupted or disturbed by defects such as porosities or cracks. This leads to an increase in temperature in the region around the defect.” Barua et al. (2014, p. 80) used this information to build a set up that would monitor the surface temperature of the deposit with a CMOS camera to look for sudden deviations of the surface temperature to locate defects during deposition. (Barua et al., 2014, p. 80.) Barua et al. (2014, p. 77) used an SLR (Single-lens reflex) camera to obtain images of the deposited track and approximated the temperature of each pixel by using RGB (Red, Green, Blue) values and radiant surface temperature. The temperatures in each pixel were obtained by calibrating the RGB values of the camera with known measured temperature readings (Barua et al., 2014, p. 81). Figure 16 shows calibrated RGB values with known temperatures.

R	G	B	Temperature (Celsius)
2	1	251	650
0	2	254	700
0	145	254	750
0	223	255	800
0	255	255	850
15	255	244	900
212	255	252	950
167	254	250	1,000

(a)



(b)

Notes: Calibration of RGB values vs. actual temperature of stainless steel substrate at 650° to 850°; color gradient change with increase in temperature (in color)

Figure 16. Calibration of RGB values with color temperature (Barua et al., 2014, p. 81).

2.9 Monitoring the height and geometry of the melt pool

Monitoring the height of the melt pool can give valuable information about the process that can be used as a feedback to control the process. Controlling of the melt pool height can be used to maintain accuracy of the part and therefore costs of post processing can be reduced. (Xing, Liu & Wang, 2006, p. 6663.) By analyzing the height of the melt pool, roughness of the parts can also be determined (Xing et al., 2006, p. 6664). Since the DED processes manufacture parts layer-by-layer, control of the deposit thickness or height of the deposit of an individual layer of the part is critical to the quality of the product (Mazumder et al., 2000, p. 403). Mazumder et al. (2000, p. 403) demonstrated that the thinner the layer thickness is, the better the surface quality is. Height control of the height of an individual layer is mainly done by visualizing, measuring and controlling the size of the melt pool during the deposition process (Mazumder et al., 2000, p. 403).

2.9.1 CCD

Toyserkani et al. (2006, p. 633) used a CCD-based optical detector to monitor the melt pool. Toyserkani et al. (2006, p. 633), placed the CCD camera normal to the process zone. In addition to the height of the melt pool, other information that can be extracted from monitoring the melt pool by a CCD-camera is the solid/liquid interface angle. According to Toyserkani et al. (2006, p. 635), Gilgien and Kurz reported that this: “angle can be used to determine the rate of solidification” of the melt pool. According to Toyserkani et al. (2006, p. 636): “the microstructure of the solidified clad is directly dependent on the rate of solidification” (Toyserkani et al., 2006, p. 636). Therefore the microstructure of the clad could be estimated when the solid/liquid interface angle is known (Toyserkani et al., 2006, p. 635).

According to Toyserkani et al. (2006, p. 633) during the process: “different light wavelengths from visible to infrared wavelengths are emitted”. Toyserkani et al. (2006, p. 634) used an interference filter with 500-700 nm bandwidth and a neutral filter to filter out undesired wavelengths. The images of the process were grabbed by a frame grabber which preprocessed the images from 640 x 480 pixels to 350 x 350 pixels, decreased the brightness and increased the contrast, to reduce computational time. The images were then fed into a pattern recognition algorithm to extract the height and angle data of the process. A pre-processed image from the process zone and a binary image from where height and angle data are extracted from can be seen in Figure 17. (Toyserkani et al., 2006, p. 634.) The height of the clad is calculated from the amount of bright pixels in the column of the matrix. The angle of liquid/solid interface can also be calculated from the binary image by calculating the angle between a reference line and the border of the bright area. (Toyserkani et al., 2006, p. 636.)

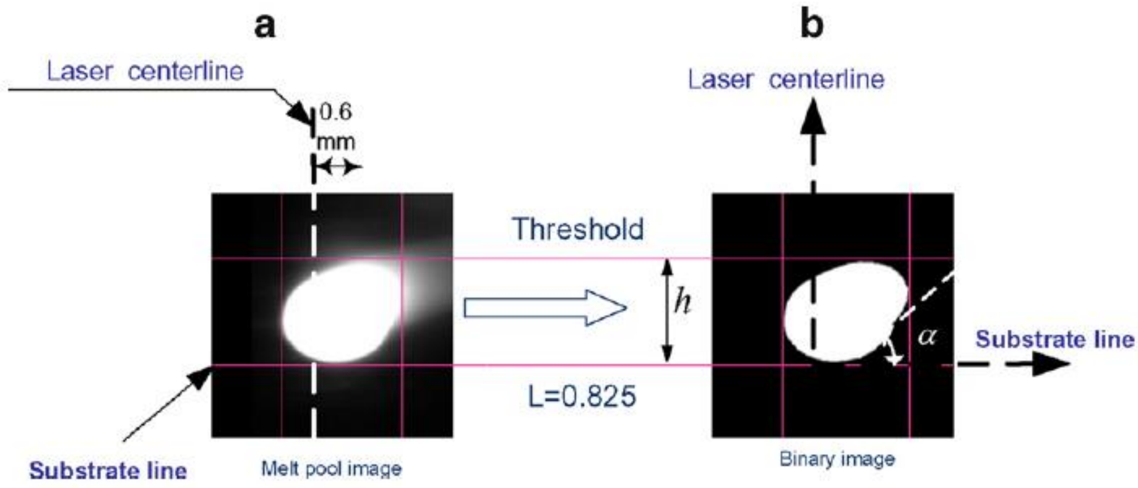


Figure 17. (a) A pre-processed image from the process zone and (b) binary image (Toyserkani et al., 2006, p. 634).

2.9.2 CMOS

Hofman et al. (2012, p. 2456) utilized: "a CMOS camera and software algorithms to obtain the width of the melt pool." Digital images were taken from the melt pool and according to Hofman et al. (2012, p. 2456), the images were: "transferred from the camera to the computer at a frame rate of about 200 Hz." At first single bright pixels are removed from the images. The cause of the bright pixels may usually be hot particles that occur. The images are then converted into black and white images and a selection of a threshold value is done as such that the boundary of the melt pool is more visible. (Hofman et al., 2012, p. 2456.) Hofman et al. (2012, p. 2456) found that the best approximation of the shape of the melt pool would be an ellipse. The width was obtained by multiplying the amount of pixels with the image scale (Hofman et al., 2012, p. 2456). The scale was 10.25 pixels/mm (Hofman et al., 2012, p. 2459). The original image, the lowpass filtered and thresholded image can be seen in Figure 18.

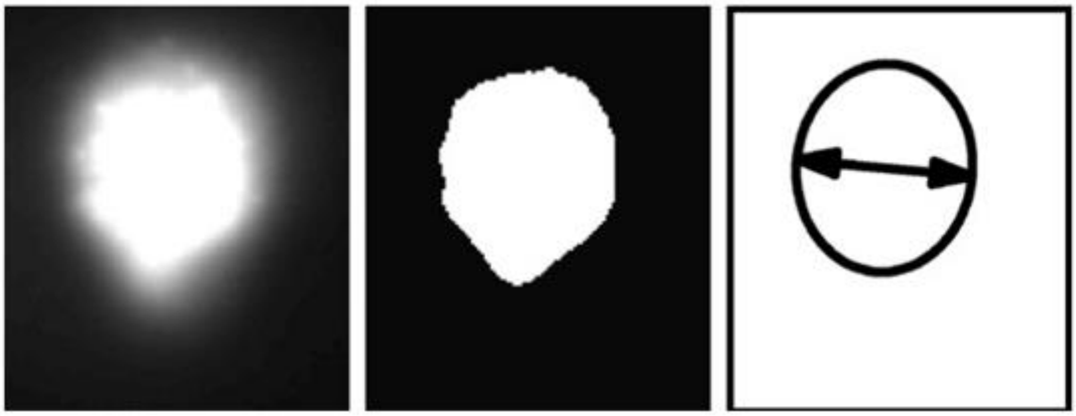


Figure 18. Left: original image. Center: lowpass filtered and thresholded image. Right: fitted ellipse. (Hofman et al., 2012, p. 2457)

Hofman et al. (2012, p. 2455) utilized a CMOS camera as a feedback sensor to build a closed loop control system that would adjust the laser power to keep the width of the melt pool at a within a desired value throughout the process. It was found that without a control system where laser power was kept at a constant value, according to Hofman et al. (2012, p. 2462) the deposited layer suffered from: “excessive dilution and reduced hardness” toward the end of the process (Hofman et al., 2012, p. 2462). When a controller was used to adjust the laser power in real time, Hofman et al. (2012, p. 2462) managed to maintain a constant dilution and a constant hardness throughout the process.

2.10 An application of monitoring and closed loop control for DED

Song et al. (2012, p. 248) built a hybrid controller that would control the melt pool temperature and the deposition height during a DED process. For the hybrid controller, Song et al. (2012, p. 248) utilized three high-speed CCD cameras in a triangulation setup to monitor the height of the melt pool and a two-color pyrometer to measure the temperature of the melt pool. A hybrid controller which utilizes both melt pool temperature monitoring and deposition height monitoring has the ability to avoid both over- and under-building of the deposited layers. According to Song et al. (2012, p. 248) over- and under-building can be a cause of: “path overlap, fluctuation of powder flow rate, geometrically dependent powder catchment efficiency, and uncontrolled heat input”. According to Song et al. (2012, p. 248) the hybrid controller is a: “two-input single-output hybrid control system that includes a master height controller and a slave temperature controller.” (Song et al., 2012, p. 248).

The height controller is a rule-based controller. According to Song et al. (2012, p. 251): “When the melt pool height is over a prescribed value, the height controller blocks the input from the temperature controller and sends a master control signal to decrease the laser power to avoid over-building.” In the case of underbuilding, according to Song et al. (2012, p. 251): “When the melt pool height is under the prescribed value, height controller is transparent and the temperature controller adjusts the laser power to maintain a constant melt pool temperature.” By adjusting the laser power to stabilize the heat input, a higher geometrical accuracy can be acquired and therefore a higher overall quality can be obtained. (Song et al., 2012, p. 248.)

Song et al. (2012, p. 254) experimented this setup by manufacturing turbine blades with and without a control system. When comparing the turbine blade manufactured with a controlled to the turbine blade manufactured without a controller, a greatly improved dimensional accuracy was obtained. (Song et al., 2012, p. 254.)

3 CONCLUSIONS

This study shows that a reasonable amount of research has been done on directed energy deposition (DED) processes, however the technologies and their development are still in their early stages and only a few commercial applications yet exist. It was found that DED could be utilized in part manufacturing where manufacturing using conventional methods would be difficult or when operating with high cost materials, where minimizing the amount of scrap material produced by conventional methods would be preferred. Combining DED processes together with conventional manufacturing methods seems to be the beneficial choice to get the best of both systems to reduce the high buy-to-fly ratio that conventional methods suffer from and to increase the dimensional accuracy and surface quality of DED processes. As found, AM processes could also be used as an alternative way of manufacturing parts from Ti-6Al-4V due to the difficulties of eliminating porosity while casting.

Although DED processes show a lot of promise, monitoring and specifically a closed loop control system for the processes was found to be crucial for the success of manufacturing the parts within the required geometrical dimensions. Due to DED processes manufacturing parts layer-upon-layer, controlling the geometry of the melt pool is essential in manufacturing the part. In addition, by analyzing the geometry of the melt pool, roughness of the part and metallurgical properties can be determined. Monitoring and collecting the data of the fluctuations in the intrinsic parameters and then compensating for the fluctuations by modifying the extrinsic parameters was found to be a method of controlling the process.

The main three areas of monitoring the process are by monitoring the powder feed rate, monitoring the temperature of the melt pool and monitoring the height and the geometry of the melt pool. Monitoring and controlling of the powder feed rate was found to be useful when manufacturing functionally graded materials. In addition, monitoring and using the monitoring data was also used to control the powder feed rate, which was found to cause changes in the geometry and the microstructure of the process. Measuring the change in weight of the powder inside the hopper, by utilizing an optoelectronic sensor or by monitoring the velocity of the particles by a CCD-camera were found to be the approaches used to monitor the powder feed rate.

Monitoring the temperature of the melt pool was discovered to give valuable information about the deposition quality, dilution, microstructure properties, mechanical properties, mass flow and energy absorption of the process. Monitoring and controlling the process was found to help protect the process from overheating and defects such as crack formation and residual porosity. Devices that could be used for temperature monitoring of the melt pool are radiation pyrometers, acoustic pyrometers, ultrasonic pyrometers, photodiodes and CMOS-cameras.

Monitoring the height and geometry of the melt pool was also found to give valuable data of the process that could be used in a closed loop control system. Controlling the melt pool height and geometry was found to help maintain the accuracy of the part, which can reduce costs of post processing. CCD- and CMOS-cameras were found to be used for monitoring the height and geometry of the melt pool. With CCD-cameras in addition to the height of the melt pool also the solid/liquid interface angle could be extracted from the images that could be used to estimate the microstructure of the part.

Although the monitoring of DED processes shows promising results and shows a large amount of potential, many of the studies done on monitoring currently have been conducted by manufacturing simple wall structures instead of structures with complex geometries. Many of the parts in the studies on monitoring were also mainly extruded parts or simple one layered builds. The possibility of utilizing multiple monitoring devices as a hybrid controller to prevent over- and under-building and to keep manufacturing conditions optimal at all times, as demonstrated by Song et al. (2012), could be the key to building complex high quality parts. One of the main requirements however is that monitoring devices that are non-intrusive to the process should be used and the data extracted from the devices should have the ability to be used in a closed loop control system.

This research only discussed ways to monitor laser based DED processes that utilized powder as the deposit material. In further studies also the use of monitoring and closed loop control in laser based DED processes that utilize wire, arc welding based and electron beam based DED processes could be researched, to gain a further understanding of monitoring DED processes and its importance.

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