LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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MULTIPURPOSE INNOVATIVE NOZZLE DESIGN FOR WIRE-FEED LASER METAL DEPOSITION

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Examiners: Professor Antti Salminen
M.Sc. (Tech) Anna Unt

ABSTRACT

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Multipurpose Innovative Nozzle Design for Wire-feed Laser Metal Deposition

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The objective of this research work is to design innovative nozzle for wire-feed laser metal deposition with integration of wire feeding nozzle, smoke suction technique and shielding gas supply all in single nozzle head. The design considers the benefit provided by wire-feed laser metal deposition compared to other AM methods.

The work was commissioned by Lappeenranta University of Technology. All the data related to design were taken from previous research works and know-how of current LMD process. Various designs were explored with design-to-use concept in mind. Progressive iterative design approach was adopted to find suitable shielding gas delivery angle and wire feeding angle along with uniform distribution of shielding gas during the process. Process monitoring sensor channel was integrated paving a way for further in-situ monitoring integration in future. Cooling of the nozzle itself was implemented with the addition of water-cooling chamber around the nozzle. Removal of process smoke and metal plumes was achieved with pressure air and suction set up integrated in nozzle right above the process area providing an opportunity to replace cross-jet feature currently used during laser processing applications.

Final design is an innovative nozzle which can be used for wire feed LMD process with improved direction independency and has integrated feature of shielding gas supply, cross-jet, shielding gas supply, process monitoring window and wire feeder nozzle.

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Suman Kafle

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LIST OF ABBREVIATIONS

3D:	Three Dimensional
AM:	Additive Manufacturing
ASTM:	American Society for Testing and Materials
BPP:	Beam Product Parameter
CAD:	Computer Aided Design
CCD:	Charge-coupled device
CMOS:	Complementary metal-oxide semiconductor
CNC:	Computer Numeric Control
DED:	Directed Energy Deposition
DP:	Diode pumped
EBF^3:	Electron Beam Freeform Fabrication
FDM:	Fused Deposition Modelling
HAZ:	Heat affected zone
IRC:	Infrared Camera
LASER:	Light Amplification by Stimulated Emission of Radiation
LMD:	Direct Metal Deposition
LMDw:	Laser Metal Deposition wire feed
LP:	Lamp pumped
Nd:YAG:	Neodymium-doped yttrium aluminum garnet
PC:	Personal Computer
PM:	Pyrometry
SFF:	Solid Freeform Fabrication

1 INTRODUCTION

Manufacturing, in general, has evolved throughout human evolution from early artistic designs to traditional machining made during industrial revolution and now all the way to additive manufacturing. The future of manufacturing is going to be different from the past as more research and efforts are made towards advanced production chains in manufacturing and greater human-robot interactions. Productivity in manufacturing workshops has been growing every passing day and advancements in manufacturing methods is at the heart of productivity. Rapid prototyping has enabled manufacturing complex parts in a fraction of time that traditional manufacturing used to take and replaced the use of large and complex one-piece precision castings to cut down production costs. Computer numeric controlled machining stations are increasingly being robotized to upscale production volume and ensure safety of work place. New opportunities bring newer challenges and demand novel advancements in existing technologies. The aim of this study is to develop laser nozzle advancement in the field of additive manufacturing which is helpful in increasing the production using AM.

1.1 Background

Additive manufacturing is a way forward to building parts with simpler design features using fewer components in future. Laser metal deposition in general provides an unique opportunity to fabricate metal parts without the limitation of part size and deposition speed unlike powder bed fusion. Options to deposit metal using laser are based on metal powder deposition and wire deposition with both having their own sets of benefits and drawbacks over the other. Wire feed laser metal deposition is sensitive to the wire position and orientation and feeding direction relative to the melt pool. Research articles and process modifications are quite common for powder metal deposition compared to wire metal deposition process because of this process sensitiveness. However, higher deposition efficiency and cleaner process environment provides the foundation to increase the use of wire feed laser metal deposition. The topic of this thesis is formed to address the nozzle set up simplifications used during wire metal deposition process making it least direction dependent to encourage the use of this process for LMD.

1.2 Research Problem

The major problem with current set up of wire metal deposition is the use of separate modules for different aspects such as wire feeding nozzle, shielding gas and process monitoring windows along with laser beam passage nozzle. This leads to movement complications during deposition process making it direction dependent and also makes the process requiring individual set up and wirings for different modules. There is also the need for cross jet feature to ensure the safety of laser optics. Nozzle with few of these features integrated has been developed and are in use for powder laser metal deposition but nozzle optimization in wire feed LMD has been limited. So, the research problem for this thesis is: *Is it possible to design wire feed LMD nozzle with wire feed nozzle, shielding gas, process monitoring window integrated to it which takes into account process parameters of wire feed LMD?*

1.3 Objective

The main objective of this research is to *design a wire feed LMD nozzle which is capable of replacing the cross-jet requirement with compressed air and suction system for smoke and dust removal*. Other objectives include *integration of wire feeding nozzle, shielding gas channel, basic process monitoring window and cooling system for nozzle to make wire feed LMD least direction dependent.*

1.4 Scope

The scope of this research is delimited to the nozzle used for wire feed LMD process. Powder-fed LMD is taken as a reference but this work itself is focused on optimization of nozzle for wire feed LMD. Position of nozzle is also limited to 5 mm away from molten pool to account for maximum amount of smoke produced during LMD process. Wire feed nozzle in this design is restricted to feed metal wires of one mm diameter irrespective of material composition. Wire feeding angle is not limited during design phase because of complexity of design integration. However, feeding angle is aimed to be as large as possible compared to the surface of the workpiece to make the nozzle system. This research is also limited to CAD modelling with required features and printing of FDM model at the end. However design is done with proper consideration as if the final metal part is manufactured with PBF. Approximate angles and distances are used as reference in this design which can be modified in the model later to match the requirements during metal printing.

2 LITERATURE REVIEW AND STATE OF THE ART

2.1 Additive Manufacturing

Additive Manufacturing (AM) is a process of joining materials to make parts using digital data of a 3D model, usually layer by layer, opposed to subtractive manufacturing and formative manufacturing methodologies (ISO/ASTM 52900 2015). AM goes by many names such as 3D printing, direct digital manufacturing, additive fabrication, rapid prototyping and solid freeform fabrication. The term AM, in general, describes additive manufacturing processes in the broadest possible way including AM for prototyping of parts, concept parts, as well as functional parts that can be used straight into industrial applications. (Guo & Leu 2013, p. 215).

The development of AM originated in the early 1980s (Kruth 1991) and since then through extensive research works, it has been used in different commercial and defense applications such as military equipment, aerospace, automotive, biomedical and energy fields (Guo & Leu 2013, p. 215). There are different types of AM processes used today depending on the way layers are added. ASTM divided AM processes into seven different categories namely: binder jetting, material jetting, powder bed fusion, directed energy deposition, sheet lamination, material extrusion and vat polymerization (ISO/ASTM 52900 2015). There are different versions of AM names given for similar process however most commonly used names are Fused deposition modeling (FDM), Inkjet printing (IJP), Laminated object manufacturing (LOM), Laser engineered nets shaping (LENS), Stereolithographic (SLA), Selective laser sintering (SLS) and Three-dimensional printing (3DP) (Huang et al. 2012, p. 1192-1193). Processes differ based on the way additive layers are added. Some use thermal energy from laser or electron beams directed via optics to melt metallic/plastic powder while some others use ink jet printing heads to spray binder or solvent onto ceramic/polymer powder. This thesis work focuses on Laser metal deposition (LMD) process which is a common name for laser based DED process.

Many materials ranging from metals and plastics to recent wood fibers are used in AM depending on the AM process being used. Plastics are mainly used for rapid prototyping while metals are used for prototyping actual commercial applications. Table 1 shows some limited commercial metal alloys used in AM but the need for development for newer alloys is there to exploit the advantages of AM and increase wider acceptance of AM (Frazier 2014, p. 1920). This research is focused on metal alloys since they are better at producing ready-to-use commercial applications.

Table 1: Selected Commercial metal alloys used in AM (according to ASTM standard where available) (Mod. Frazier 2014, p. 1920)

Titanium	**Aluminum**	**Tool Steels**	**Super Alloys**	**Stainless steel**	**Refactrory**
Ti-6Al-4V	Al-Si-Mg	AISI H13	Inconel alloy 625	316 & 316L	MoRe
Ti-6Al-4V ELI	A6061	Cermets	Inconel alloy 718	ASTM TYPE 420	Tantalum/Tungsten alloy
Comercially Pure (CP) Ti			Stellite	ASTM TYPE 347H	ASTM F75
Gamma TiAl				PH 17-4	Alumina

2.2 Laser Metal Deposition (LMD)

Different names for Laser Metal Deposition (LMD) are used in industrial and research world such as Laser engineered nets shaping (LENS), Laser solid forming (LSF), Direct light fabrication (DLF), Selective laser powder remelting (SLPR) and Laser metal deposition shaping (LMDS) (Dinda et al. 2009, p. 98) (Zhang et al. 2012, p. 104). However, the basic principle for all of these techniques remains same. Laser energy is fed along with powder injection or wire injection in coaxial or off-axial setup to form a molten pool on the substrate or previously deposited layer. The injected powder or wire is melted either before entering the melt pool via laser-material interaction on the way to melt pool or after reaching the molten pool. This melt pool results in creation of solid metallic components through layer by layer deposition of melted metal powder or wire. (Zhang et al. 2012, p. 104.) High spatial resolution of the well-defined laser beam along with the state of art LMD has been growing to challenge building near net shape components straight from their CAD files (Kovacevic et al. 2016, p. 24) and also for repair manufacturing jobs. Figure 1 below illustrates the basic working principle of LMD.

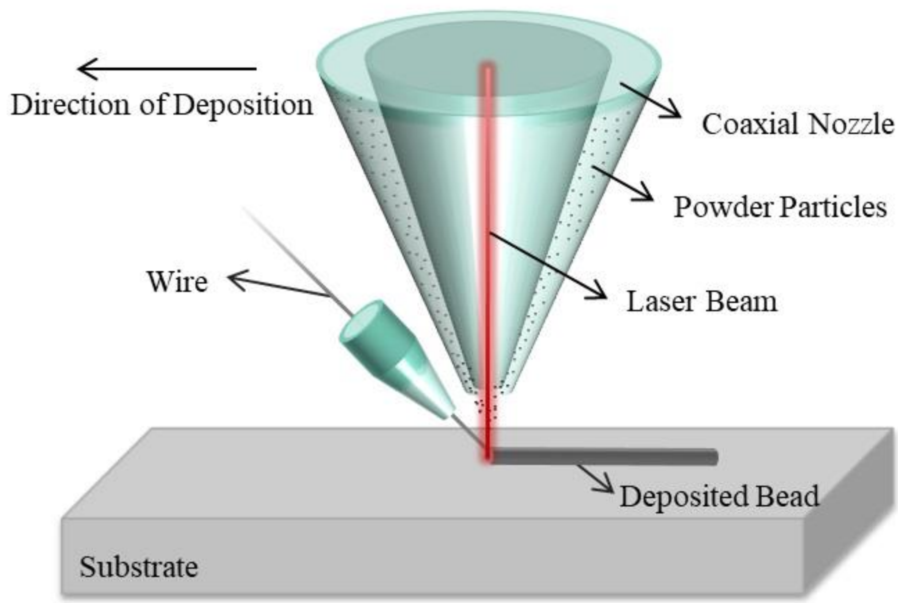


Figure 1: Schematic representation of laser metal deposition (Oliari et al. 2017, p. 467).

The process itself is similar to laser cladding where laser beam is used to melt the filler metal (powder or wire) onto a working substrate. Deposited metal pool solidifies quickly through heat dissipation in substrate creating a solid profile. Typically high power lasers such as fiber and diode laser are used to deposit metal powder. The substrate is then moved along x, y, and z direction relative to laser and nozzle head to achieve a desired 3D shape. There are two types of metal feeding process in LMD which will be discussed in next section.

LMD, unlike other additive manufacturing processes, is high precise metallic equipment manufacturing process which does not require any structural support and rafting because of its multi-axis laser and substrate movement mechanism. The process itself depends on number of different parameters ranging from laser parameters and process parameters to feeding parameters. These parameters are controlled mainly using non-contact closed loop feedback control system similar to the one suggested by Mazumder & Voekel 1995. There have been recent developments in LMD using predictive algorithms in combination with closed loop feedback system to provide real-time error anticipation and correction which control parameters according to necessity to obtain optimum height and surface quality (Srivatsan & Sudarshan 2015). These systems are advancements to traditional open loop control system where optimum LMD parameters are decided with trial and error basis after series of laboratory experiments. Sub-sections below provide detailed review of parameter effects of LMD, movement mechanisms, laser types used in LMD process and recent advancements in the field of LMD.

2.2.1 Powder feed LMD vs Wire feed LMD

LMD has two ways of feeding metal into substrate melt pool. One is wire feed where metal wire is fed mostly with off-axis feed nozzle making some angle with laser beam while other is powder feeding mostly done coaxial with laser beam. Figure 2 below shows two different feeding systems for metals.

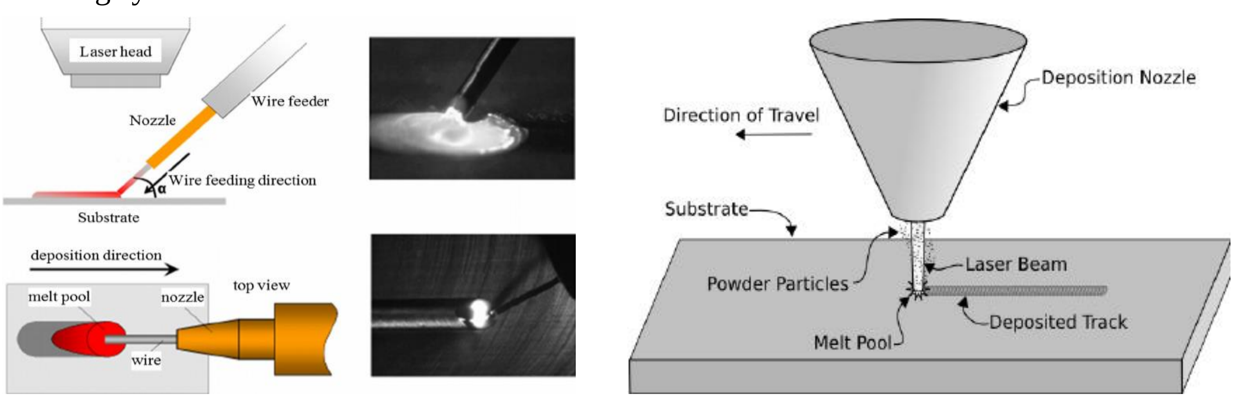


Figure 2: Off-axial wire feeding (left)(Heralic 2012, p.17) vs coaxial powder feeding (right) (Fan & Liou 2012, p. 5).

Wire feeding and powder feeding both have their own merits and demerits. Powder feeding is popular for higher dimensional accuracy, complex geometries and producing functionally graded materials (FGM). Ding et al. (2015, p. 466) claims that components with powder feeding is high in precision (± 0.05 mm) and surface smoothness (9-16 μm) but extremely low in deposition rate with deposition rates of around 10g/min. Meanwhile wire feeding process is 100% material usage efficient with deposition rate of up to 330g/min achieved for stainless steel, but it has lower dimensional accuracy compared to powder feeding. These advantages and drawbacks of different processes leads to a trade-off between high deposition rate and high resolution while selecting the type of feeding system for LMD. (Ding et al. 2015, p. 466.) To overcome this drawback there has been few other experiments combining both powder feeding and wire feeding in LMD process. It has been reported that deposition rate of 87% higher than those of either powder and wire feed alone can be achieved with wire and powder deposition by laser (WPDL) (Pinkerton et al. 2007).

Comparison between two feeding process for popular laser metal deposition process are illustrated in Table 2 below. Due to the lack of data, Electron beam freeform fabrication (EBF[3]) is used instead of wired laser metal deposition for comparison.

Table 2: Comparison of some LMD processes with different feeding techniques (Mod. Ding et al. 2015, pp. 467).

Additive Material	**Process**	**Layer thicknes(μm)**	**Deposition rate(g/min)**	**Dimensional accuracy(mm)**	**Surface roughness(μm)**
Powder	Laser Consolidation	-	1-30	< ±0.069	1-2
	DLF	200	10	±0.13	20
Wire	EBF[3]	-	Upto 330	Low	High

Wire feed is comparatively dust free during LMD process even though smoke and metal plumes are likely to arise during the process. Small powder particles from powder feed are likely to fly around during LMD process which increases the chance of health-related issues. Higher cost of metal powders makes powder feed LMD process comparatively expensive than wire feed LMD. As mentioned earlier higher deposition rate is the most unique advantage of wire feeding over powder feeding. However, wire feed LMD has some limitations such as radiation absorption dependence on surface finish of wire, reduced variety of materials and higher dilution rate of deposited material with the substrate (Oliari et al. 2017, p. 467).

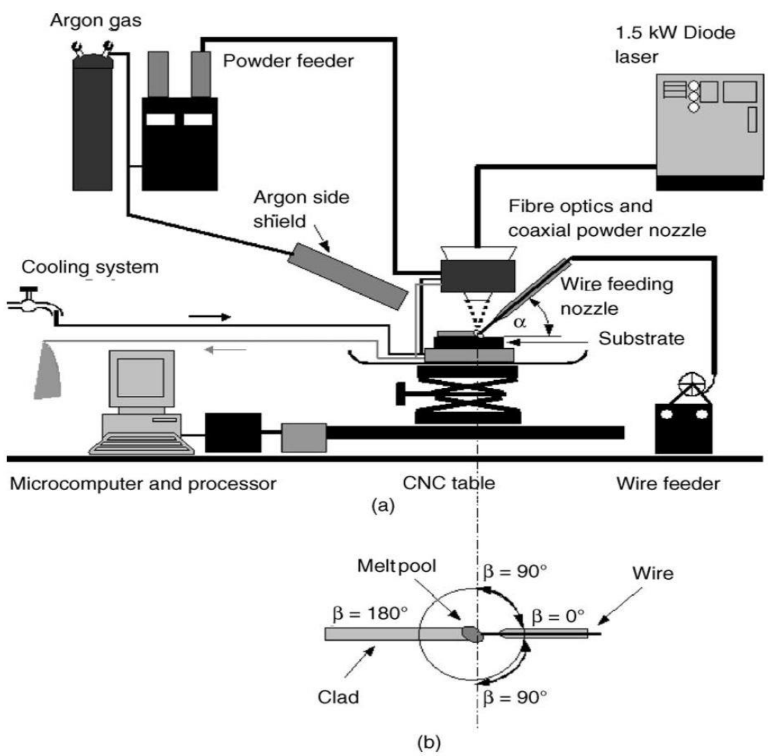


Figure 3: Powder and Wire feeding set up showing wire injection angles in (a) vertical plane and (b) horizontal plane (Syed et al. 2005, p. 4804).

Thorough analysis of coaxial powder feeding, off-axial nozzle wire feeding, and combined powder-wire feeding was done by Syed et al. (2006, p. 4804) using 1.5 kW diode laser to deposit 316L stainless steel in powder and wire form. Laser beam with diameter of 1.5 mm was used to deposit wire of diameter 0.6 mm and powder with particle size of 53-150 μm diameter and the ratio of 1:1 was maintained for combined deposition of wire and powder. Setup used for this experiment is shown in Figure 3. Results showed that the mixture of powder and wire feeding produced better surface roughness with increased deposition efficiency unlike decrease in surface roughness when deposition efficiency increased in powder only setup. This phenomenon was explained as an effect of larger and hotter pool due to higher deposition efficiency of combined deposition taking more time to reach quasi steady state before solidification that resulted in increase of surface roughness. Wire feeding angle α with respect to vertical plane had inverse relationship with surface roughness for combined material delivery with surface roughness (Ra), decreasing by almost 5 μm when vertical angle was increased from 20 to 43 degrees. Moreover, with increasing feeding angle to horizontal plane, β, from 0 to 90 degrees for wire feed alone resulted in drop in deposition efficiency from 70% to almost 35% and also increase in surface roughness. The drop in deposition efficiency was explained due to resistance offered to the wire by the solidifying melt pool as the angle increased. With angle more than 90 degrees (rear feeding), wire entered from the rear of melt pool and partially confront the solidifying edge of the melt pool causing slippage at delivery wheel and formation of serrations. (Syed et al. 2006, p. 4805-4806.)

Earlier experiment under similar condition by Syed et al. (2005, p. 268-276) where powder was also fed with varying off-axial nozzle positions found out that feeding angle with powder has greater flexibility of almost 0 to 180 degrees (for both front and rear feeding) compared to 20 to 60 degrees for front feeding and 120 to 160 degrees for rear feeding of wire for a similar clad quality. Also, it was found that good clad was obtained with wire feeding done from leading edge of melt pool compared to center or trailing edge of the melt pool.

2.2.2 Movement Mechanism

With the advancements in machining and additive manufacturing sector, computer numeric controlled (CNC) 5 axis movement is preferred over traditional CNC 3 axis movement. In LMD, 5 axis movement is achieved with the combination of robot containing laser deposition head and fixed working base or fixed laser head with CNC controlled working base. The ability of freeform fabrication of complex parts without the need of any support structure is possible because of precise multi-axis movement mechanism. The basic configuration of laser and motion table is illustrated in Figure 4. Sharp and accurate movement mechanism is a must during freeform fabrication techniques which are direction dependent such as wire feed LMD process to always maintain the best feeding direction.

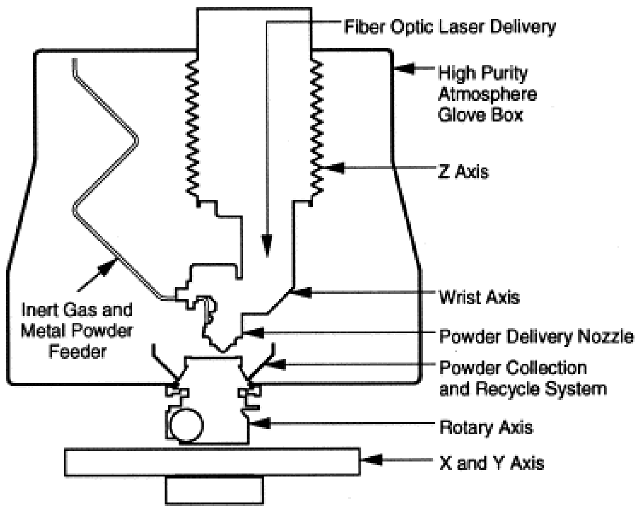


Figure 4: Multi axis motion system used in LMD (Milewski et al. 1999, p. 20).

In the Figure 4 above, 5 axes movement are achieved with x-y movement of table, z movement of laser head, rotary movement with rotary axis and wrist axis for angular movement.

2.2.3 Parameter Control Mechanism

LMD process is dynamically complex and it requires constant monitoring of process inputs such as laser power, material feed rate and process speed along with resulting outcome of LMD process like melt pool dimensions and temperature to produce near net shape geometry. Control and prediction of single-track layer has been researched from early 1980's while the real challenge in LMD lies in prediction and geometry control of multiple layer deposition. Addition of layer changes thermal behavior of the preceding layer thereby making it challenging to anticipate accurate geometry. Closed-loop and open-loop are most commonly used parameter control mechanisms during LMD process.

Open loop Process Control

Open loop system in LMD basically means a system where the operator inputs constant initial process parameter and the system fabricates the part irrespective of in-process fluctuations. It has input feature, but no output feedback associated with it. The equipment used for open loop control feedback is the same set up used for LMD process without the addition of vision based or temperature-based sensors. “If the real-time monitoring signal is not used for controlling the processing parameters (e.g. power, speed, powder feed rate), the monitoring system is called an open-loop system” (Purtonen et al. 2014, p. 1223). Hu & Kovacevic (2003, p. 52) highlighted that processing parameter have complex relationship in open-loop metal deposition which results in varying width of molten pool. It is hence difficult to perform 3D metal deposition with constant wall thickness using predefined laser power for the laser cladding process.

However, few open loop research works have been carried out either as an independent open-loop experiment or to compare it with closed-loop feedback system to study the phenomenon of laser deposition process. As studied by Sammons et al. (2017, p. 8) open-loop deposition was not able to track the reference height during the deposition process thereby resulting in rippled layers in the final geometry. In comparison, height deviation for the closed-loop deposit was minimal with smooth depositions in every layer.

Closed Loop Process Control

Often referred to as in-situ monitoring, this method implements real time process data to improve geometrical accuracy of components built by LMD. Parameters such as powder flow rate, laser power and process speed are used to control process properties like melt pool geometry and temperature. There have been several studies since 90’s in the field of closed loop feedback system including use of CCD cameras, pyrometer and infrared imaging. Some of them are discussed below.

Hu & Kovacevic (2003) used controllable powder delivery with real time sensing and control of powder delivery rate during fabrication of functionally graded materials. Infrared image sensing was also used to control heat input resulting in controlled molten pool. It has been stated that the use of coaxial laser mounted CCD camera has big advantage for molten pool sensing because of larger field of view and omni-directionality with clear view. An optoelectronic sensor consisting of photo diode, a laser diode and a glass window was used to measure the powder flow rate in real time. The sensor used the principle of powder diffusion and reflection to determine the powder delivery rate with laser energy captured by photo diode decreasing with increase in powder delivery rate with inverse linearity. (Hu & Kovacevic (2003, p. 52.) The basic principle of this sensor setup and schematic of the whole experimental set up is presented in Figure 5 and Figure 6.

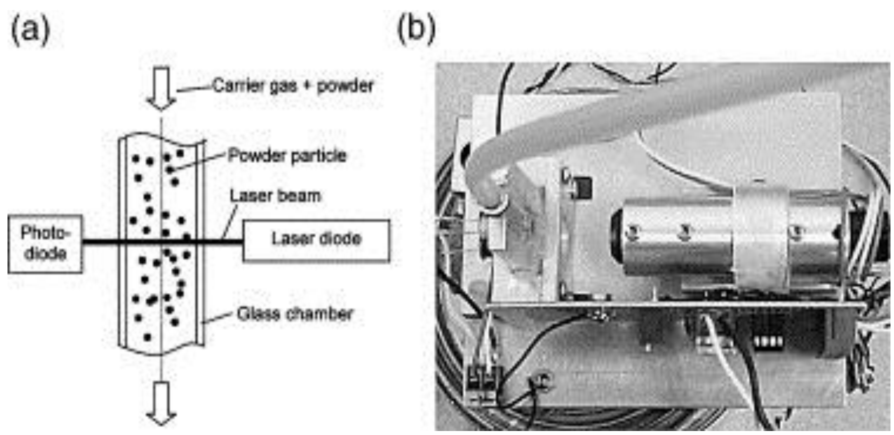


Figure 5: Powder delivery rate sensor. (a) Schematic of the sensor. (b) Setup in the experiment (Hu & Kovacevic (2003, p. 52).

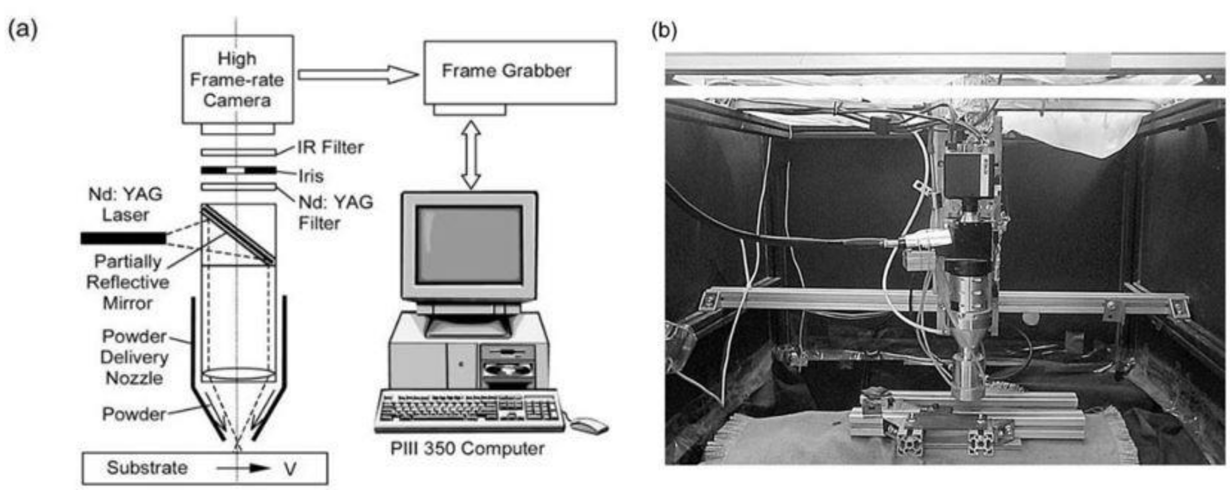


Figure 6: Infrared image acquisition system. (a) Schematic. (b) Experimental set up (Hu & Kovacevic (2003, p. 52).

Powder delivery and accurate powder feed velocity control is a difficult task which has led the researchers to explore the control of melt pool geometry, melt pool temperature and uniform microstructural properties. Early work done by Mazumder et al. (2000) presented detailed analysis of height control during LMD with the use of three lens located at 120 degrees in x-y plane (experimental set up shown in Figure 7). Three collecting lenses were fiber-pigtailed to

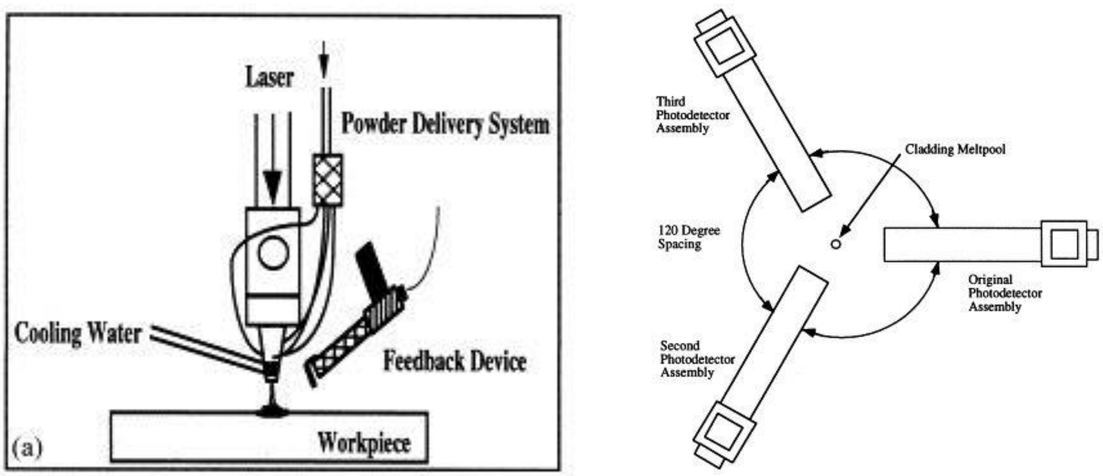


Figure 7: Set up and schematic of height controller feedback used by Mazumder et al. (2000, p. 403, 405).

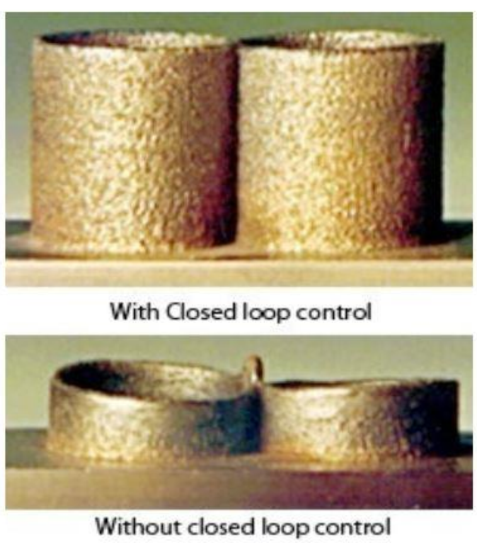


Figure 8: Example of fabrication with closed loop control and without closed loop control (Mazumder et al. 2000, p. 404).

three CCD cameras to capture build height in real time. Control logic ensured the robustness of cladding height once the result of two out of three cameras fulfilled the preset reference height to be achieved for each layer. The result was uniform layer height as can be seen in Figure 8. (Mazumder et al. 2000, p. 403-405.) However, the effect of melt pool temperature and cooling rate was not taken into account in this study.

Another important factor which needs to be controlled with closed feedback system is melt pool geometry. Research from Colodron et al. (2011) used field programmable gate array monitoring system instead of PC-based solutions in combination with maximized frame rate CMOS camera to measure melt pool dimensions (height and width) and degree of dilution (the relation between melted area of the substrate and the amount of added powder). However, this setup lacked real time processing ability.

Research led by Mazaffari et al. (2013) used intelligent metaheuristic technique called Particle Swarm Optimization (PSO) in combination with CCD camera for feedback closed loop control to control clad height and melt pool depth in real time. Laser power and process velocity optimization was altered to acquire desired melt pool geometry. Similar experiment made by Tang et al. (2010) used pyrometer and empirical model with first order melt pool temperature transfer function to adjust laser power between successive deposition layers with the feedback of melt pool temperature and height from IR sensor and laser displacement sensor. However, with each increasing layer, temperature profile changes and the effect of this heat behavior change was not accounted for, which resulted in wavy non-uniform morphology. Use of generalized predictive controller (GPC) with two-input single-output was proposed by Song & Mazumder (2011). Three high speed CCD cameras in combination with dual-color pyrometer connected to feedback with master height controller and a slave temperature controller was used to control melt pool height and temperature. This hybrid controller was able to stabilize layer growth by avoiding over building and compensate under-building through heat input control. The schematic of LMD process and height controller logic used by Song & Mazumder (2011) is shown in Figure 9. Recent research by Farshindianfar et al. (2016) had developed real time measurement of cooling rate and temperature of melt pool to control microstructure formation in real time using infrared thermal imaging system which is essential to maintain the quality of parts fabricated with LMD process.

Configuration with all important feedback monitoring system in LMD was recently proposed by Chua et al. (2017) as shown in Figure 10. The proposed set up allowed accurate measurement of melt pool geometry (width, length and height) and temperature profile to be drafted in real time using high speed camera (melt pool geometry image), pyrometer (temperature at a single point) and IR camera (melt pool temperature profile) after the data are processed by data acquisition system.

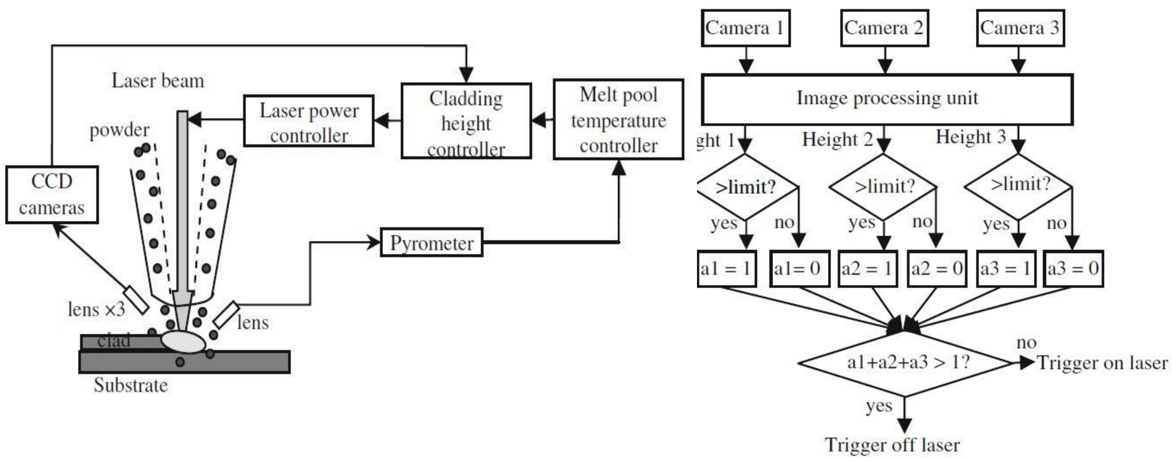


Figure 9: Schematic of LMD process with closed loop control (left) and logic of height controller with three high speed cameras (right) (Song & Mazumder 2011, p. 249).

The list of major process monitoring during LMD process used by various researchers over the time was assembled by Purtonen et al. 2014 and is presented in Table 2. All of the reported studies used continuous wave laser beam and were studied to monitor work piece and/or melt pool (Purtonen et al. 2014, p.1224).

Table 2: Process monitoring with LMD processes (Mod. Purtonen et al. 2014, p. 1224). ***Sensor Type****: PM=Pyromtery, CCD=CCD camera, CCD(NIR)=CCD camera filtered for near infrared wavelengths, IRC=IR camera.* ***Material:*** *MS=Mild and low carbon steel, SS=Stainless steel, MMC=Metal matrix Composite.* ***Target:*** *Work piece=Area larger than Melt pool*

Sensor Type	**Process**	**Laser**	**Material**	**Target**
CCD(NIR)	DED	Nd:YAG	MS, Tool Steel	Melt pool
PM	DED	CO_2	SS	Melt pool, Work piece
IRC, PM, CCD(NIR)	Cladding	CO_2	MMC, MS	Melt pool
CCD	DED	Fiber	Ti	Melt pool
CMOS	DED	Fiber	TI	-
CCD	Cladding	Fiber	MS, SS	Melt pool
PM	DED	Nd:YAG	MS, SS, Ni-alloy	Melt pool
CMOS, PM	Cladding	Nd:YAG	MS, SS, Stellite	Work piece

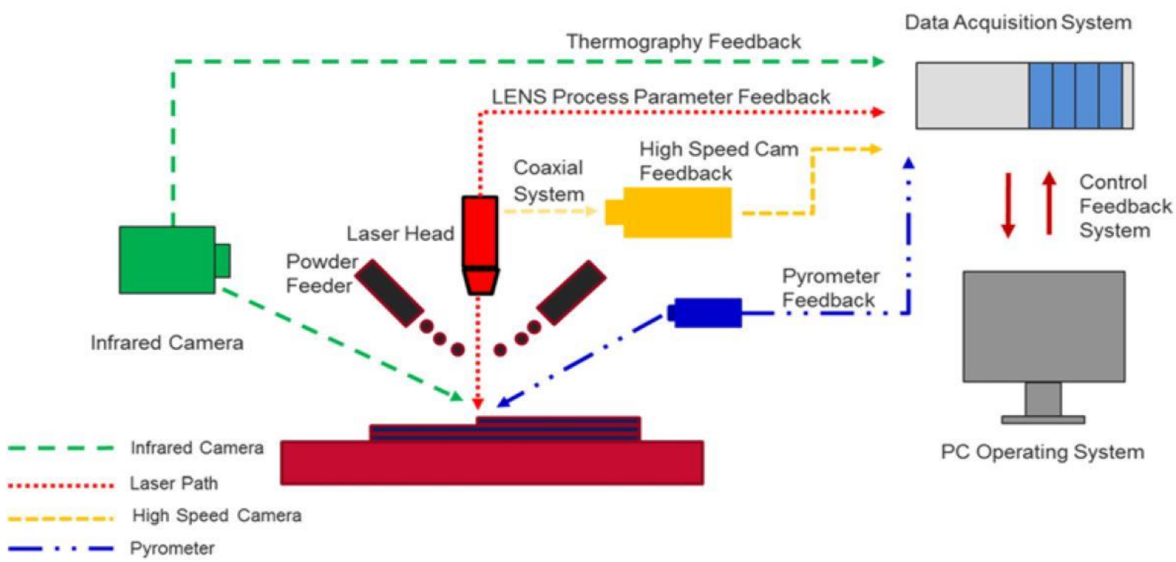


Figure 10: Configuration of the proposed LMD monitoring system (Chua et al. 2017, p. 241).

2.2.4 Laser system used in LMD

LASER stands for Light Amplification by Stimulated Emission of Radiation. A laser generally consists of a gain medium, a pumping energy source and an optical resonator where gain medium placed inside the optical resonator amplifies the light by stimulated emission using the external energy supplied by a pumping energy source. Gain medium can be solid state, gas, semiconductor or fiber. (Lee et al. 2017, p. 309.) High power laser have high precision leading to its widespread use in material processing. Laser metal deposition as the name suggests use high power laser beam to melt the additive material to produce 3D parts. Most common laser sources for metal additive manufacturing methods used today are fiber delivered disk laser and diode laser. Earlier researches however were used to be done with CO_2 and Nd:YAG laser as well. Fiber laser, which is more commonly used in LMD is explained in detail.

Table 3: Comparison of industrial lasers used in material processing applications (Mod. Majumdar & Manna 2013, p. 72-73) (IPG Photonics 2018) (Trumpf 2018). ***LP****:* Lamp pumped, ***DP****:* Diode pumped

Laser / **Parameter**	**CO_2**	**Nd:YAG**	**Fiber**
Wavelength	10.60 µm	1.064 µm	1.070 µm
Efficiency	5-20%	LP: 1-3%; DP: 10-20%	30-50%
Output Power	Upto 20 kW	Upto 4 kW	Upto 100 kW
Pump source	Electrical discharge	Flash lamp / laser diode	Laser diode
BPP (mm.mrad)	3-5	18-20	0.3-4
Fiber delivery	Not possible	Possible	Possible

Table 3 continues: Comparisions for industrial lasers used in material processing applications (Mod. Majumdar & Manna 2013, p. 72-73) (IPG Photonics 2018) (Trumpf 2018). ***LP****:* Lamp pumped, ***DP****:* Diode pumped

Laser / **Parameter**	**CO_2**	**Nd:YAG**	**Fiber**
Maintenance periods (hrs)	2000	200 (lamp life) 100000 (diode life)	Maintenance free (25000)
Advantages	Good beam quality, low cost, high efficiency	Higher absorption than CO_2, flexible beam delivery, less sensitive to laser induced plasma	Excellent beam quality, high efficiency, flexible beam delivery
Disadvantages	Low absorption in metals, fiber beam delivery no available	Poor beam quality at higher laser power, limited life of lamps	High cost of pump diode lasers

Fiber Laser

Fiber laser as we know of today is a high power, highly efficient, excellent beam quality, compact size and long life laser source which has come a long way since its invention in 1961. It is the most promising laser source in additive manufacturing which use optical glass fiber doped with rare-earth element such as ytterbium (Yb), Neodymium (Nd) and Erbium (Er) as an active gain medium. Ytterbium has small difference in pump and laser photons energies also known as quantum defects which results in high quantum efficiency (94%) making it more common in laser material processing. (Mazumdar & Manna 2013, p. 79.)

Operation principle is similar to solid state diode pumped Nd:YAG laser as fiber laser is also pumped by laser diodes in 950-980 nm wavelength to produce laser beams with 1070 nm output wavelength with double-clad fiber as gain medium (Lee et al. 2017, p. 310). The major advantage of this laser type is its flexibility in beam delivery via optical fibers which led to its supremacy over CO_2 laser and Nd:YAG laser during laser metal deposition. All-fiber technology makes it immune to misalignment and yields in robustness against environmental disturbances. Parallel combination of several fibers can produce up to 100 kW power commercially with high beam quality (Kawahito et al. 2018. p. 4667). High electrical-to-optical efficiency in the range of 30-50% for Yb-doped fiber laser is the main reason for increased use of fiber laser instead of CO_2 and Nd:YAG laser in rapid prototyping and other laser material processing applications. The schematic of Yb-fiber laser is shown in Figure 11 below. (Mazumdar & Manna 2013, p. 82-83.)

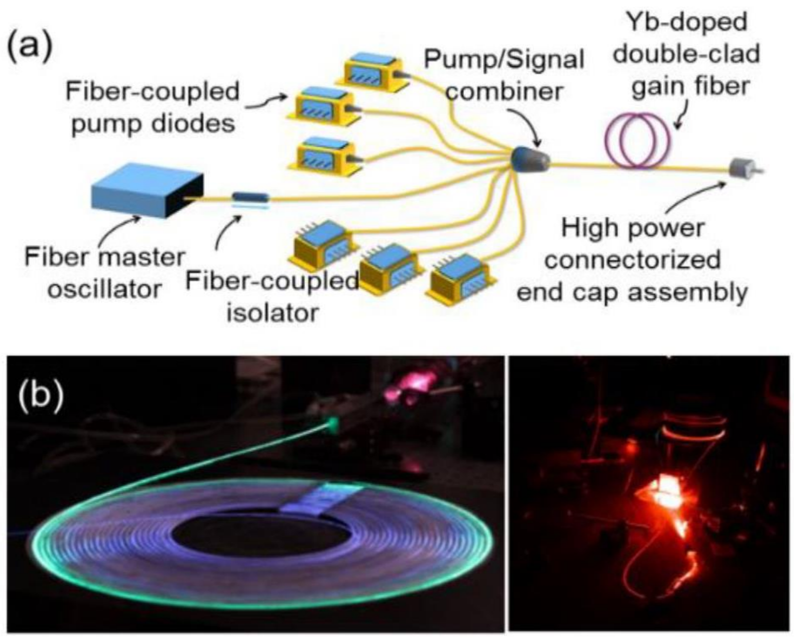


Figure 11: a) Schematic of a Yb-fiber laser, b) Commercial Yb-fiber lasers under operation (Lee et al. 2017, p. 310).

2.2.5 Parameters influencing wire feed LMD

As discussed earlier there are numbers of different parameters including laser parameter, process parameters and powder characteristics that influence the size and geometric uniformity of deposited metal structure using LMD. According to Song & Mazumder 2011 laser power, process speed, beam size and powder flow rate are dominant parameters in determining dimensional accuracy and metallurgical properties while parameters such as bead overlapping, layer increment, gas flow, powder flow profile, tool path design and powder quality are secondary parameters. Similarly, Brandl et al. 2011(b) used laser power, welding speed and wire-feed speed factor (wire feed rate/welding speed) as process influence factors during single bead wire feed micro-structural analysis. Wire feed direction is the most common research topic when it comes to wire and laser additive manufacturing evident by research articles made by Ding et al. 2015 and Syed & Li 2011 to determine the bead dimensions and quality. In this section the influence of laser power, wire feed rate and process speed on LMD process and their significance in LMD process with respect to different metals used is discussed.

Laser Power

Laser power is an important part of wire and laser additive manufacturing process since it is directly related with wire melting ability during the process. Mok et al. (2008), demonstrated the relation between laser power and clad profile (bead height and width). It was clear that higher laser power led to increase in deposition width and height, for same process speed compared to lower laser power. Laser power moreover was also influencing wire feed rate. Complete melting of additive wire was achieved at wire feed rate of 2 m/min for 2.06 kW and 1.65 kW power and wire feed rate of 1 m/min for laser power of 1.2 kW for 1.2 mm wire diameter of Ti-6Al-4V. Brandl et al. (2011(a), p. 1127) findings suggest that with increasing laser power, rate of solidification reduces, leading to increased grain columnar size. Hence the microstructural properties of single beads are also affected by the change in laser power. Literature review analysis by Ding et al. (2015, p. 470) however reported that with the increase in laser power, deposition height decreases, and deposition width increases without having significant effect on overall deposition area. These influences of parameters are tabulated in Table 4. Review made by Miranda et al. (2008) acknowledged the fact that for the same laser power, narrow beam with the diameter similar to wire diameter increases process speed and wire feed rate compared to larger beam diameter. The setup is also more efficient because the heat is concentrated in melting the wire without affecting substrate and resulting lower heat affected zone. However, there is a risk of process collapse if the wire deviates from the center of the beam.

Table 4: Influence of process parameters on dimension of single beads (Mod. Ding et al. 2015, p. 470). ↑: significant increase, ↓: significant decrease, 0: no significant influence

Bead profile / Parameter	Deposition area	Deposition height	Deposition width
Power ↑	0	↓	↑
Welding speed ↑	0	↑	↓
wire feed rate/welding speed ↑	↑	↑	0

Wire Feed Rate

The speed at which filler wire is fed into LMD process is of crucial importance to obtain stable and desired deposition profile. Xiao et al. (2002) research using 5 kW CO_2 laser indicated that with the increase of the wire feed rate, the deposited layer decreases in both trailing and leading direction of filler wire made up of AlSi12. This phenomenon occurs because energy requirement to melt the metal wire increases with the increase in wire feed rate but since the laser power is constant it leads to reduced energy interaction resulting in smaller weld profile and improper weld (Xiao et al. 2002).

With constant laser power of 2.06 kW, the wire feed rate was changed from 0.83 m/min to 3.33 m/min by Mok et al. (2008). For weld speed below 100 mm/min, weight of deposit was directly proportional to up until certain wire feed rate with difference in deposition weight of up to 4g between wire feed rate of 0.86 m/min and 2.22 m/min. This pronounced difference was however reduced to less than 1g with increase in process speed above 100 mm/min. It was clear that the wire feed rate had minimal impact in deposition mass if the process speed is too high and the impact was proportionally more at lower welding speeds. Material used for this experiment was Ti-6Al-4V. (Mok et al. 2008.)

Process Speed

Sometimes referred as deposition/welding speed, process speed is a fundamental parameter in determining good deposition profile. Too high process speed leads to lack of penetration and incomplete melting of filler wire while lower speed leads to higher dilution and greater heat affected zone (HAZ). Xiao et al. (2002) found that with the increase in process speed, bead width and area of deposition is reduced for both leading and trailing direction under CO_2 laser. Penetration depth was also on decrease after process speed was exceeded above 4 m/min and 5 m/min for leading and trailing edge wire feeding. This change in dimension behavior was quite similar to the relationship with the change in wire feed rate. Explanation for this was the increase in process speed resulted in reduced energy intensity which led to decrease in weld profile.

Mok et al. (2008), further backed this research finding with Nd:YAG laser on titanium substrate. It was found that with the increase in process speed from 0.5 m/min to 2.5 m/min, for a constant laser power, clad height decreased by more than 70%. The same was true for clad width but the effect was less with only 10% reduction in the width.

Wire feed angle and direction

Miranda et al. (2008) discussed about wire feeding angle and distance between the wire tip and the substrate. With low feeding angle and less distance between wire tip and substrate, splashing of molten material can be prevented and the melt pool remains continuous and smooth in geometry. Syed & Li (2005), one of the pioneering research group in LMD, found out that the front feeding was the best wire feeding direction when using stainless steel as material feed. Rear feeding caused severe undulations in the track surface with periodic serrations along the deposited track. Clad was also better when wire was fed at the leading point of the melt pool in both front and rear feeding compared to wire positioned at center or trailing edge of the melt pool. Wire feeding angle was found to be limited within 10°-75° for front feeding with 20°-60° producing best clad quality.

Mok et al. (2008) had similar results to Syed & Li (2005) in terms of clad quality and serrations occurring during rear wire feeding with titanium alloy filler wire. Moreover, deposition weight was compared between front feeding, side feeding and back feeding with different wire feeding angles. Front feeding with 45° feed angle had best deposit of 6 grams at 100 mm/min process speed. Back feeding with 60° feed angle produced similar deposit weight of 5.7 grams and side feeding with 15° deposited 6.6 grams for 100 mm/min process speed.

Front feeding at 45° was more consistent in terms of both clad quality and deposition weight. (Mok et al. 2008.)

However, Xiao et al. (2002) carried out welding with aluminum substrate and aluminum filler wire the effect of feeding direction to be opposite of earlier presented research. Wire feeding at trailing edge resulted in increased penetration and deposit profile with more stable and efficient process compared to leading edge. Therefore wire feed direction and angle depends on the material used during the process hence altering these parameters results in good quality LMD deposition (Ding et al. 2015, p. 469).

2.2.6 Current wire feed LMD set up

Current set ups used for wire feed LMD use laser beam source, off-axial wire feed nozzle connected with wire feeder, shielding gas channel and fume extractor all with their own separate channels acting without a single movement mechanism. A sample demonstration used for wire feed LMD set up used by Demir (2018) can be seen below in Figure 12. Individual explanations about various aspects of wire feed LMD currently in use are presented below.

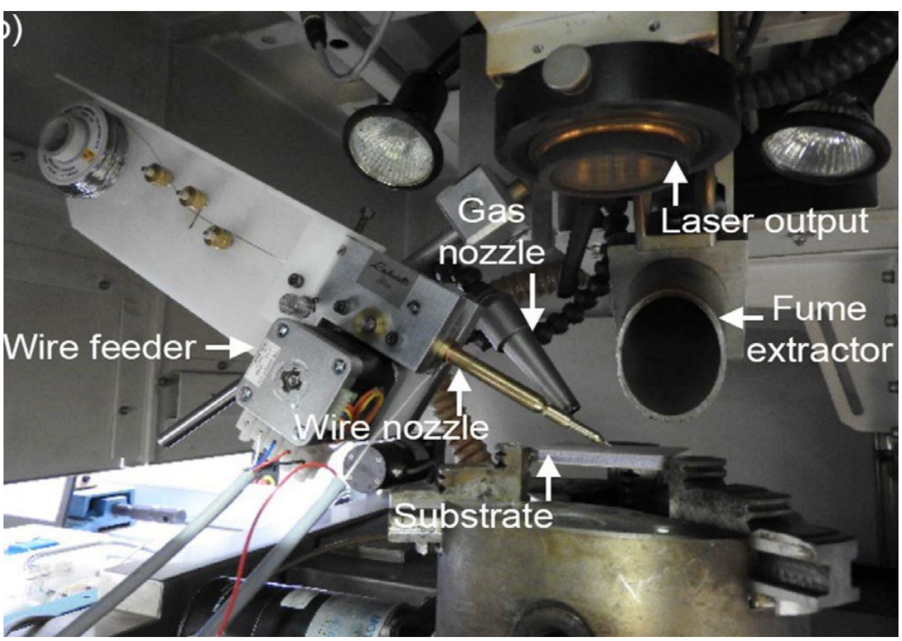


Figure 12: Wire feed LMD set up used by Demir (2018, p. 11).

Laser

Laser source used in LMD process is primarily fiber laser and diode laser. The fact that shorter wavelength of laser resulting in higher absorption in metal plays significant part in a broader use of short wavelength laser in both power feed LMD and wire feed LMD. Also fiber delivery of laser makes it easier for set up of process and beam is of excellent quality in fiber laser and diode laser. Well renowned companies such as Coherent Inc., Trumpf, IPG Photonics and Han's laser are the market leader in supplying laser equipment for LMD process with each company exceeding one billion dollars revenue from laser solutions in 2016 (Laserfocusworld, 2016).

Syed & Li (2005) used Laserline LDL 160-1500 1.5 kW diode laser for wire feeding metal deposition of stainless steel to research the effects of wire feeding direction. Beam focal length used was of 300 mm with beam dimensions 2.5 mm × 3.5 mm. Similarly, 2.5 kW Rofin DL025 diode laser was used by Mok et al. (2008, p. 3934) with beam size of 2 mm × 7 mm in focus for deposition of titanium alloy Ti-6Al-4V. Froend et al. (2018, p. 722) used 8 kW continuous wave Yb fibre laser YLS-8000-S2-Y12 (IPG Photonics Corporation) to deposit 5087 aluminum alloy. Kim & Peng (2000, p. 300) used 5.5 kW Nd:YAG laser with circular beam diameter of 2.5 mm to experiment the effect of wire feeding direction and position, cladding time, and cladding speed on the quality of cladding layer with Inconel. Brandl et al. (2011(a), p. 1121) used Trumpf HLD 3504 Nd:YAG rod laser (diode pumped) for microstructure analysis of wire-feed additive layers of titanium alloy Ti-6Al-4V. Kelly & Kampe (2004, p. 1862) however used 11 kW CO_2 laser for microstructural evolution study in LMD. So the wide variety of laser sources are in use for wire laser metal deposition depending on material and laser availability.

Wire feeder

Current option for wire feeding LMD process has separate off-axial wire feeding channel directed towards melt pool. Wire composition depends upon the metal requirements used to create a new part or repaired parts. Frequently used materials for wire feed LMD are similar to powder-fed LMD materials. Materials available for LMDw in wire feedstock are titanium and alloys, Inconel 625, nickel and copper nickel alloys, stainless steel 300 series, aluminum alloys and alloy steel to name a few (Sciaky 2018). Automatic wire feeding is done during the process with industrial wire feeders such as Weldaix wire feeder (Brandl et al. 2011(a), p.1121), Planetics 501 feeding head and wire feeder (Mok et al. 2008, p. 3934), or F4 replacement arc wire feed unit manufactured by Technical Arc (Syed & Li 2005, p. 519). Wire feeder WF200DC by Redman Controls & Electronics Ltd. was used as a second wire feeder in research work carried out by Medrano Tellez (2010, p. 80). Wire feeding is done mostly straight into the melt pool where wire melts because of laser heat and melt pool temperature.

Shielding gas

Shielding gas is an important supplementary feature to ensure new layers manufactured with LMD do not undergo oxidation. Current set ups mostly use argon as shielding gas supplied separately into the melt pool or supplied coaxially to the wire. Syed & Li (2005, p. 519) used argon coaxially with the feed wire while another setup used by Brandl et al. (2011(a), p. 1121) also used argon as shielding gas flooded from the base of an open box. Whole set up was kept in argon atmosphere with off-axial argon feeding by Syed et al. (2005, p. 269) for their experiment. Kim & Peng (2000, p. 300) used argon to cool the nozzle and shield molten metal but directed from another channel opposite to the wire feeding direction.

Air Suction

Special air suction technique integrated into nozzle itself has not been implemented to the best of knowledge available from recent research works. However, cross jet feature is used to blow away rising smoke from the process area which is located above the nozzle section and just below laser optics in many industrial wire feeding LMD set ups. Fume extractor is another process accessory used for smoke removal in wire feed LMD currently in use. It is mostly set up in an off-axial position near the process area as seen in Figure 12. This is quite effective way to make the process smoke free and protect laser optics from contamination. However, there is some smoke around the process area until cross jet feature blows it away making a room for improvement in this aspect.

Movement unit

As mentioned earlier in movement mechanism section, flexibility with movement during LMD process is achieved with either with CNC table with multi axis motion or with multi-axis robot. Usually 4-6 axis of motion is preferred for LMD process depending on the complexity of the manufacturing aimed to be carried out and direction dependency. For example straight thin walled structure requires just three axis movement in x, y and z direction while complex shapes with angular layers need rotational axes in addition to linear x, y and z axis movement. Wire feed LMD process is achievable with modifications on other laser manufacturing work stations such as those designed for cutting, drilling or engraving by changing wire feed nozzle and laser head with same CNC table and robots to control LMD movements.

Earlier studies made by Mok et al. (2008, p. 3934) and Syed et al. (2005, p. 269) used CNC table with four and two axis movement respectively for laser cladding while Brandl et al. (2011(a), p. 1121) used high accuracy 6-axis robot, Kuka KR 100 HA, for wire-feed additive layer manufacturing. Froend et al. (2018) used CNC-supported XYZ machining center (IXION Corporation) for aluminum LMDw. Multi-axis robot gives better flexibility but is expensive compared to modifying existing CNC table for LMD movement mechanism.

Nozzle

The main purpose of nozzle is to protect laser beam from unwanted interaction during LMD process. Most powder fed nozzles are multipurpose in functionality as shown in Figure 14 (b), with coaxial powder feeding and shielding gas input integrated in the same nozzle design. However, wire feed LMD has not been carried out with this kind of multipurpose nozzle in industrial and research works. The closest multipurpose nozzle used for wire feed LMD process has been developed by Fraunhofer IWS and ILT which has been used by Ocylok et al. (2016) to investigate laser metal deposition of stainless steel 316L. It used beam splitting optics to divide laser beam in three parts and focus them back to molten pool with converging lens and feed wire and shielding gas coaxial to laser beam in the center axis. General schematic of coaxial wire feeding developed by Fraunhofer is shown in Figure 13. (Ocylok et al. 2016.)

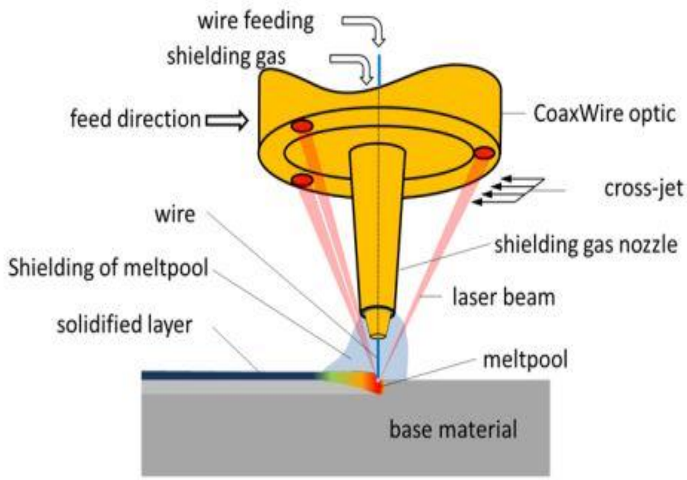


Figure 13: Schematic of cladding with coaxial nozzle (Ocylok et al 2016).

3 NOZZLE DESIGN

3.1 Functional Requirements

The main idea of this thesis is to design a single innovative nozzle comprising of wire feeder nozzle head, shielding gas, cross jet vapor and plume removal outlet for wire feed laser metal deposition. Various studies and innovations have been made for powder feed nozzles which has led to nozzles with multiple powder feeding options such as off-axial and coaxial feeding

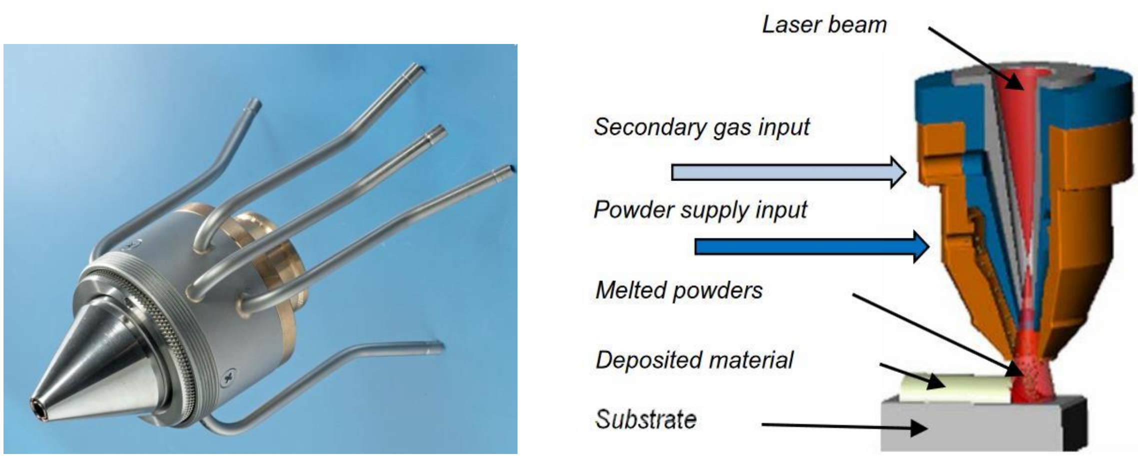


Figure 14: (a) Coaxial powder feed nozzle with replaceable nozzle tip (left) (Fraunhofer 2018) and (b) schematic of IREPA patented coaxial nozzle (right) (Boisselier et al. 2014, p. 241).

along with coaxial shielding mechanisms. Basic powder feed nozzle with integrated feature of powder feeder nozzle and shielding gas designed by Fraunhofer ILT is demonstrated in Figure 14 (a). But similar approach and design is yet to be integrated for LMDw. Requirements of LMDw for this thesis work are discussed below.

Laser

Laser used for metal deposition in this design is continuous wave IPG 10 kW fiber laser with wavelength of 1070 ± 10 nm. Laser beam is short by wavelength and is fiber deliverable, suitable for laser metal applications as discussed earlier in literature review segment. The new nozzle should be designed with a clear aperture for laser beam up to 4 mm diameter once the beam starts to converge through the focusing lens. Laser beam parameters for laser used for this nozzle design are listed in Table 5.

Table 5: Laser beam parameter values used for wire fed nozzle design

Laser Type	**Fiber diameter**	**Collimator focal length**	**Focal length of focusing optics**	**Focal point diameter**	**BPP**	**Nozzle Standoff distance**
IPG 10kW fiber laser	200 µm	150 mm	155 mm	0.4 mm	<0.039 mm.mrad	5 mm

Wire feeder nozzle

One of the most important part of this nozzle design is to integrate wire feeding nozzle into the deposition head. Current scenarios of off-axial feeding have led to problems during freeform metal deposition because of dependency of layer build up on direction of deposition. Since the wire feed nozzle feeds wire off-axially into melt pool independent of cladding head, movement of the whole cladding system lacks smoothness. Current LMDw set up involving wire feeder and shielding gas has to be changed constantly with the change in movement of laser head when depositing complex shapes. This design requires to develop off-axial wire feeding nozzle with constant feeding angle of approximately 70° at every point of metal deposition. It will make the movement of whole nozzle system smooth and more integrated as a unit which makes it less direction dependent during the deposition process. The whole setup moves as a unit which makes it easier to carry out laser metal deposition. Wire diameter was selected to be 1 mm irrespective of wire composition.

Shielding gas

Shielding is an important aspect of laser metal deposition as it ensures oxidation free building platform and maintains stable weld pool geometry. Shielding gas delivery should be ensured right after the deposition along the deposition direction to make the maximum use of shielding gas to protect recently deposited layers. Composition of shielding gas used for the process is independent of the nozzle design and can be used according to the demand of the process and material being processed. Uniform distribution of shielding gas must be ensured around the built area with this nozzle design. Semi-conical ring-shaped cavity surrounding laser beam is used to distribute shielding gas using this design.

Cross jet feature

Welding and metal deposition work always produce metal plumes and smoke which are not only dangerous to on-site workers but also harmful to laser optics head if it reaches focusing optics and it also disturbs the process. This problem is solved with cross jet feature in almost every welding and cladding works which blows metal plumes away from laser optics. One recent example of cross jet used integrated with wire fed nozzle by LASERDYNE 2018 is illustrated in Figure 15. This set up by LASERDYNE 2018 has off-axial wire feeding for welding function. Usually, this set up is above the nozzle head in powder deposition and welding process which is effective in smoke prevention to laser optics but still has harmful smoke flying around the process area and contributing to unnecessary heating of the cladding and the laser head. Moreover, metal dust is also responsible for beam attenuation and making lens dirty during the welding and cladding process.

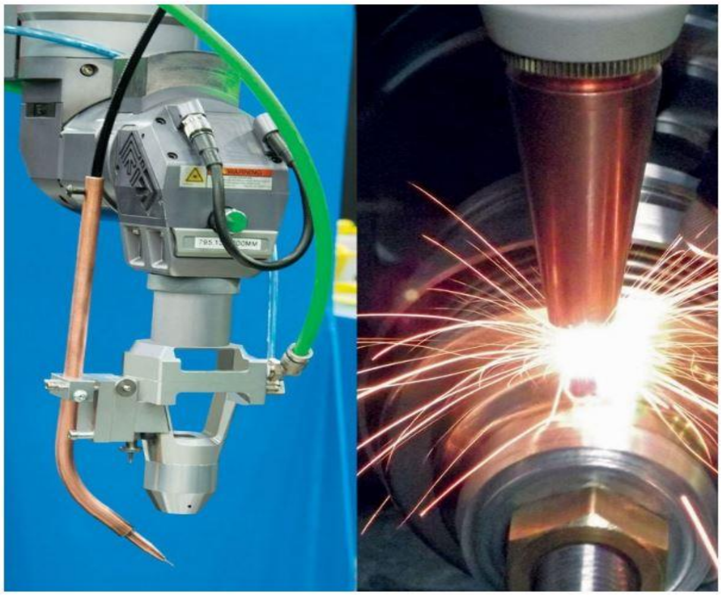


Figure 15: Cross jet feature in welding nozzle BD3Y by LASERDYNE (2015).

Focus is made to integrate this cross-jet feature with pressure air supply and smoke suction mechanism as near to the process as possible to make LMD process smoke and metal plumes free. Various designs will be modelled to ensure this characteristic which is also the main driving factor for this innovative nozzle design.

Nozzle standoff distance

Nozzle standoff distance is the distance between the nozzle and surface of work piece. This design, as stated earlier, focuses on smoke free atmosphere which is possible with near the process set up. Standoff distance for this design is assumed to be 5 mm. Focal length of laser beam is at 0 mm from the substrate surface.

Cooling

During constant exposure to laser beam and reflected metal plumes, nozzle tends to get hot during the process. Temperatures can get as high as 2500°C during metal deposition which should be considered during this nozzle design. Moreover, this nozzle has standoff distance of just 5 mm which makes it more prone to extra heating during the process. It is an additional feature to this nozzle design in addition to already existing cooling mechanisms for laser optics. With all these features in one nozzle, this design aims to simplify the wire feed laser metal deposition and open the possibility of mass scale adoption of this technology when it comes to additive manufacturing of metal materials because of its simplicity.

3.2 Concept Design

Since the nozzle idea is quite new and there are no designs which could be used as reference for this design work, concept design of what needs to be done was made with paper sketch at first. All necessary features were added with basic idea of how the nozzle should function. Sketch work is illustrated in the Figure 16. Dimension of the whole nozzle was kept undecided with an idea to make it as small as possible and as light as possible which reduces the load to optical head mounted onto. Basic design followed 60-65 mm height and 60-70 mm width at top.

As it can be seen from Figure 16, maximum wire feed angle is our target along with shielding around the deposited bead. Pressure air supply and air suction to blow out all smoke and metal vapor is applied in the nozzle itself.

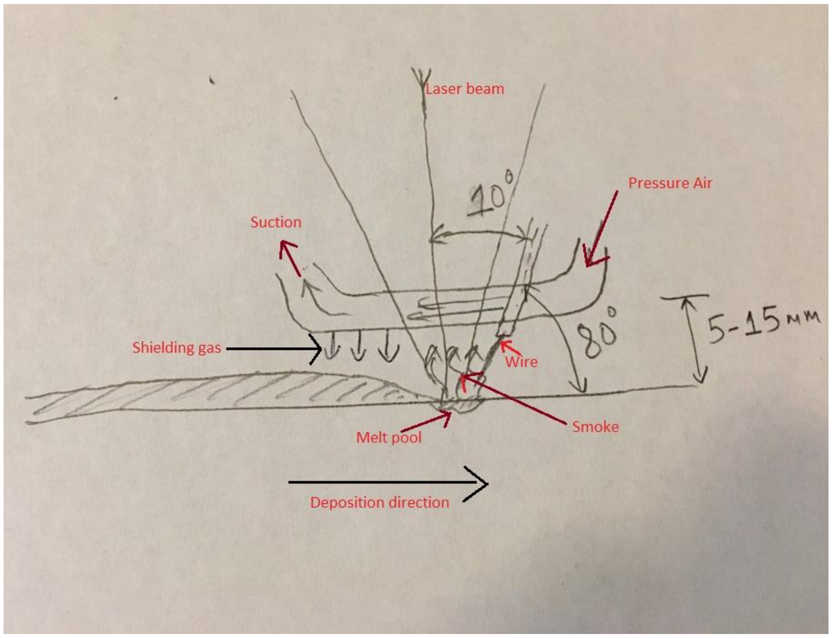


Figure 16: Initial sketch work representing basic nozzle design concept.

3.3 Design 1.0

First design model was used to integrate wire feeder unit at 80 degrees to horizontal surface along with shielding gas with conical spray around the laser beam. Shielding gas was fed through two identical holes from the top of the nozzle. The whole model had extruded top with wings to pass all the wires that feed wire and shielding gas to the system. Design 1.0 is

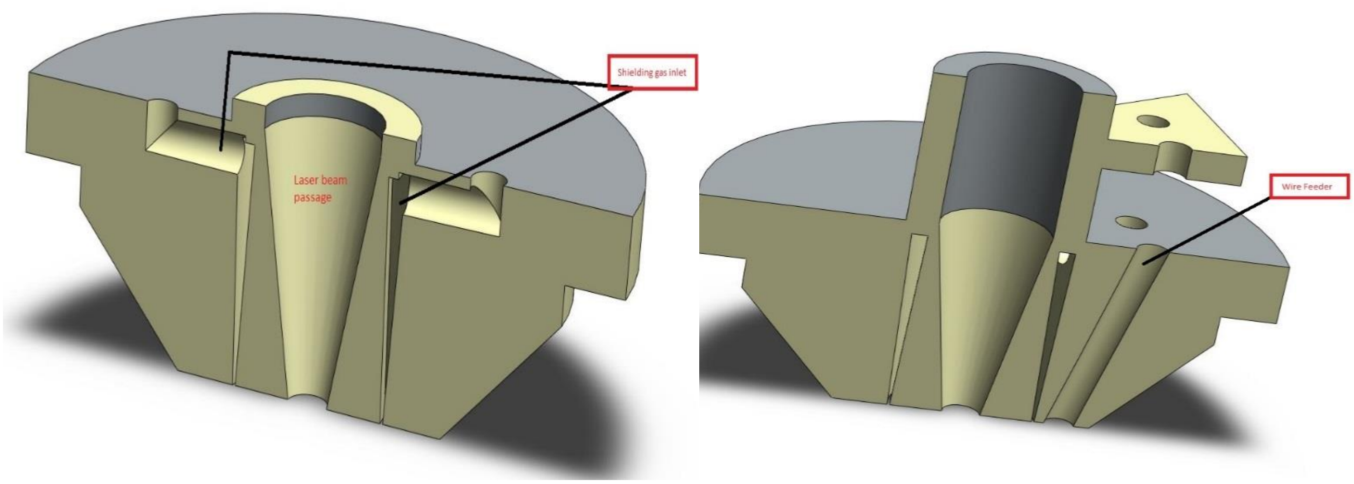


Figure 17: Basic design of the nozzle with wire feeding unit(left) and shielding gas inlet(right).

presented in Figure 17. The idea was to make it easier for nozzle movement with fewer independent cables and tubes around the nozzle. Conical shape of nozzle was retained. Before deciding on this conical shape, there was an idea for circular nozzle design (Figure 18). However, decision was made to go with conventional nozzle shape because of its ease to integrate all desired function and to give it more universal appeal. Pressure air inlet and smoke suction function were still missing from this design. Hence, second version of this design was carried out with addition of air supply and suction.

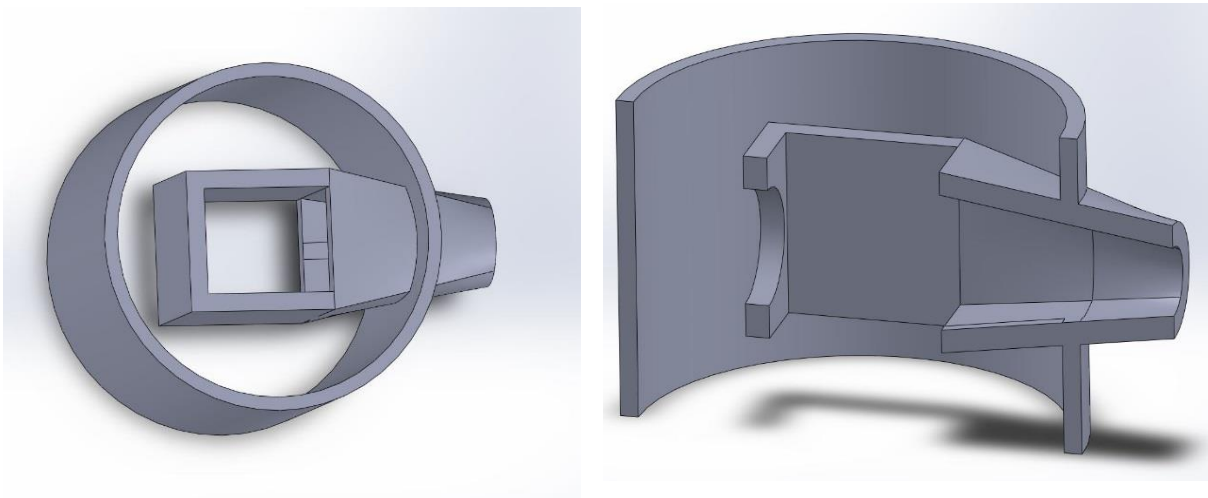


Figure 18: Circular nozzle design concept.

3.4 Design 2.0

Next version of nozzle design was carried out with pressure air supply and suction in it. Shielding gas inlet was increased to three holes symmetrical to each other. This set up helps in uniform distribution of shielding gas throughout the laser beam. Pressure inlet tube of 2 mm diameter was introduced on top of the nozzle which carried air towards base nozzle feeding through the laser passage opening. Suction system is set up right opposite to inlet opening in

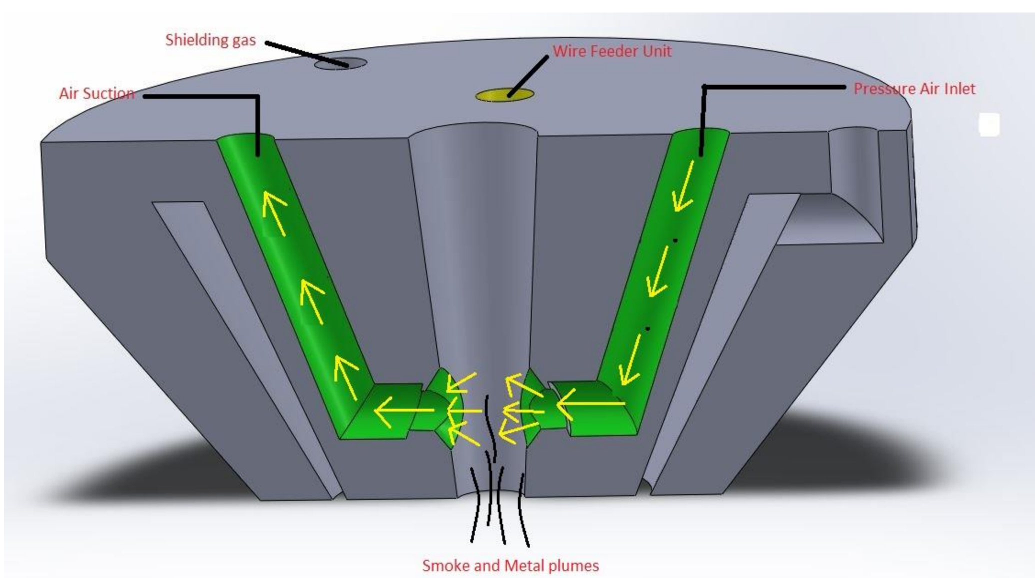


Figure 19: Illustration of air pressure and suction unit with basic nozzle.

the base of nozzle to suck all smoke and metal plumes rising upwards from the process. Suction system is assumed to be vacuum suction created by vacuum generator with estimated pressure of 200 mbar and above. Figure 19 shows this suction integration at the bottom part of nozzle (12 mm away from bottom) near the process area. As was discussed earlier about smoke free LMD process, it is necessary to have this external air blow and suction away from optic head to achieve the aim of less heating and dirt-free laser optics. Since the nozzle standoff distance is 5 mm, all the vapor and smoke likely pass through laser passage area to make this suction system effective.

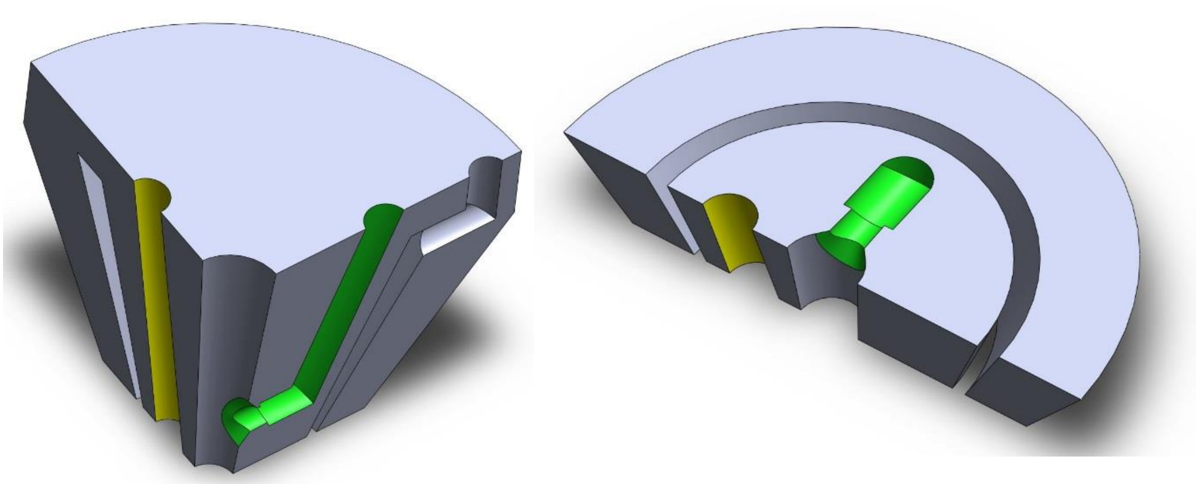


Figure 110: Double section cut of nozzle (left), and top section cut (right).

Different section cuts are shown in Figure 20 to illustrate this design even further. Figure 20 left shows double section cut with air supply (green) and wire feed (yellow) holes along with main laser beam passage. Figure 20 right shows top cross-section view demonstrating the shielding gas flow chamber along with pressure air inlet chamber. Figure 21 shows all inner holes in the nozzle design to give better idea of the design.

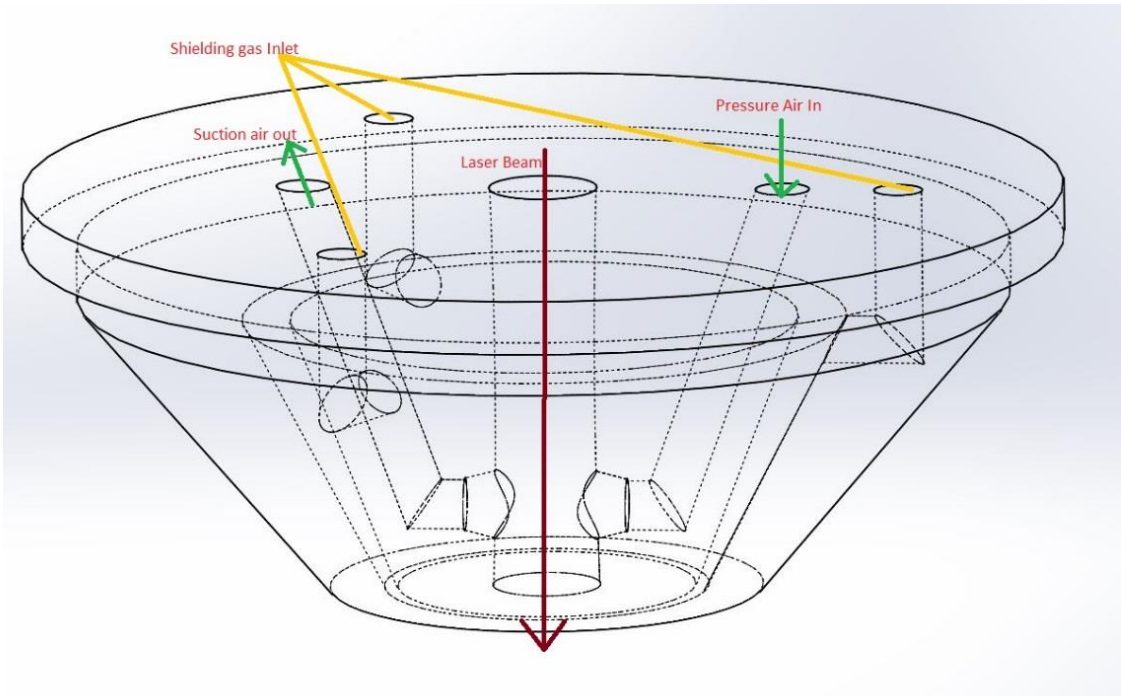


Figure 21: Wire frame illustration of inner geometrical shape of nozzle.

This design achieved basic functionality of what was aimed at the beginning of the thesis for wire feed LMD process nozzle. Nozzle cooling feature was missing from this design along with more uniform distribution set up for shielding gas inlet. Decision was made to print this model to have some idea about the functionality of the proposed design. Fused Deposition modelling (FDM) by Prenta was used with PLA 1.2 mm filament wire for this model. Plastic printed model is shown below in Figure 22. It took about two hours to print this model.

From the FDM printed model below, it was evident that this design was still with unnecessary mass which should be reduced to achieve better accuracy from nozzle. Less weight results in lesser inertia giving better accuracy for the whole laser-nozzle set up. Steps towards final design work was evident through this design so the missing cooling function should be bundled in the same design to prevent nozzle from overheating during the processing.

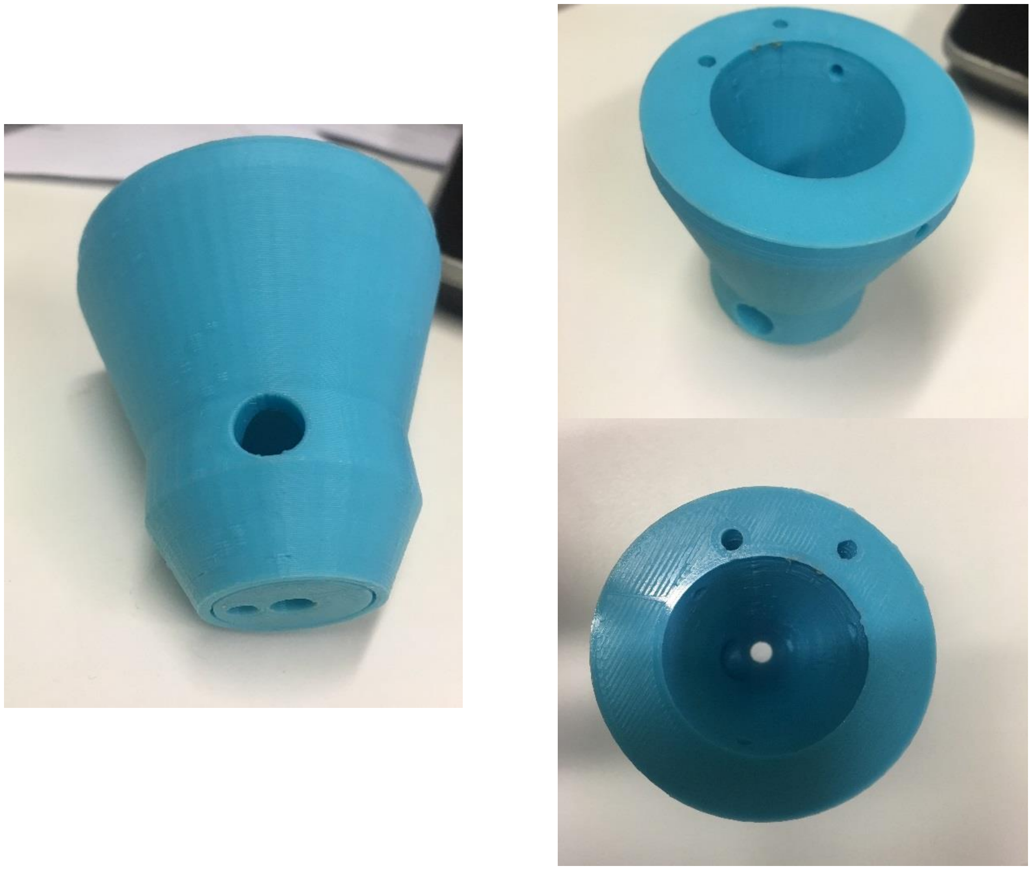


Figure 22: FDM printed prototype of design 2.0.

3.5 Design 3.0

Design of next version of nozzle started with reducing the volume of nozzle itself. Thin walled laser beam passage was created with separate tubes carrying shielding gas to the base of the nozzle. Circular tubes for shielding gas were of same inner diameter (2 mm) as earlier holes with 1 mm wall thickness. Air pressure inlet tubes were moved to bottom part of nozzle along with suction tubes and the suction hole was made two times larger than inlet hole. Suction hole was chamfered to give greater cross section area when smoke is pulled off from the system. This gives more space to create a vacuum and therefore extract smoke and metal flyers efficiently.

Wire feed is done through one edge of the nozzle which acts as a front edge during LMD process. Shielding was decided to cover trailing edge during LMD process hence semi-circular design around laser beam was created with three shielding gas inlets at top supplying with three independent tubes all the way down to nozzle bottom below air pressure inlet and air suction outlet openings as can be seen from Figure 23 and Figure 25. Smoke chamber was also introduced in this design to capture maximum smoke from the process right inside the nozzle bottom part and sucking it out from there. Figurative comparison of smoke chamber from this design and earlier model is illustrated in Figure 24.

During the LMD process, almost all smoke and plumes are blown away from the nozzle with air supply and suction system. However, it is quite possible to have some smoke leakage from laser beam passage all the way up to laser optics sometimes. This unexpected yet possible

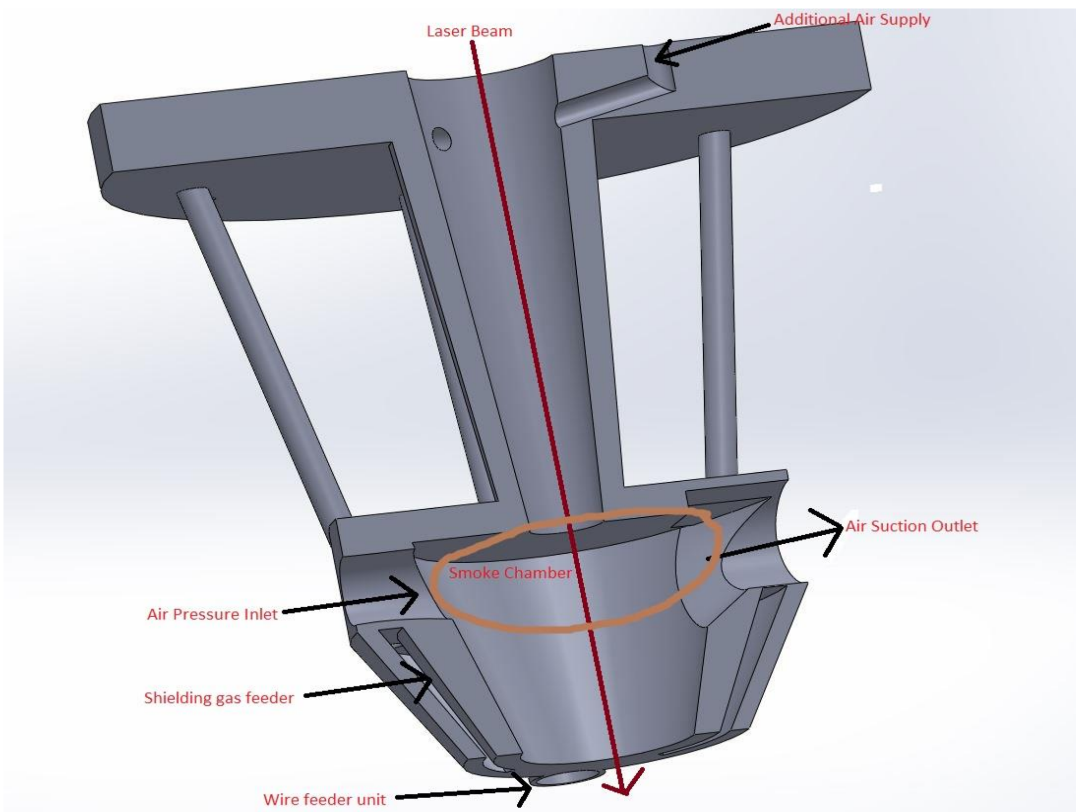


Figure 23: Nozzle 3.0 design with illustration of new changes.

drawback of this design is taken care with additional air pressure blown into the nozzle from top of the nozzle head as shown in Figure 23. This air flow pushes any accidental smoke leakage back into the smoke chamber where suction pressure pulls it away from nozzle. It is a fail-safe model designed for smoke free LMD process, thereby ensuring that no extra cross jet feature is needed in this set up.

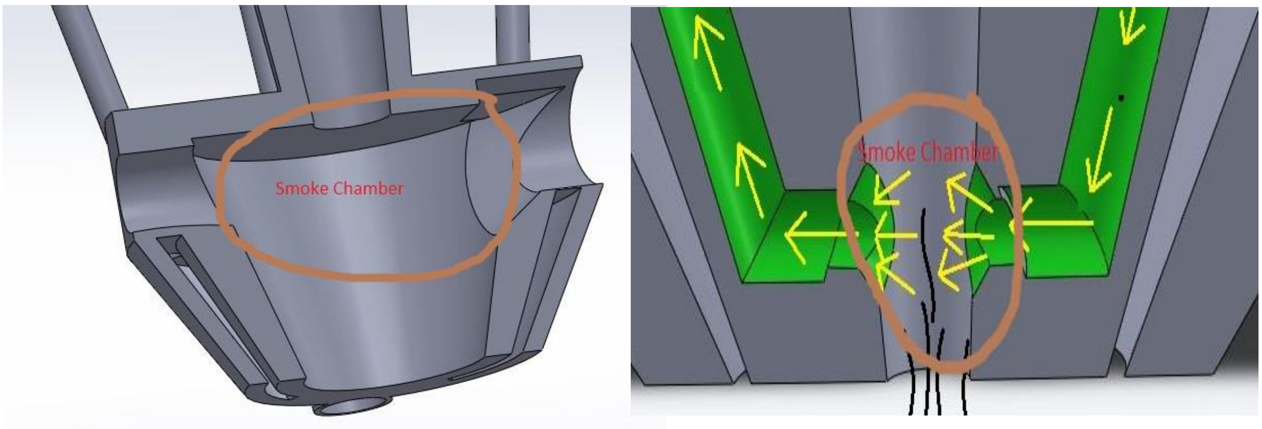


Figure 24: Smoke chamber of design 3.0 (left) compared to design 2.0 (right).

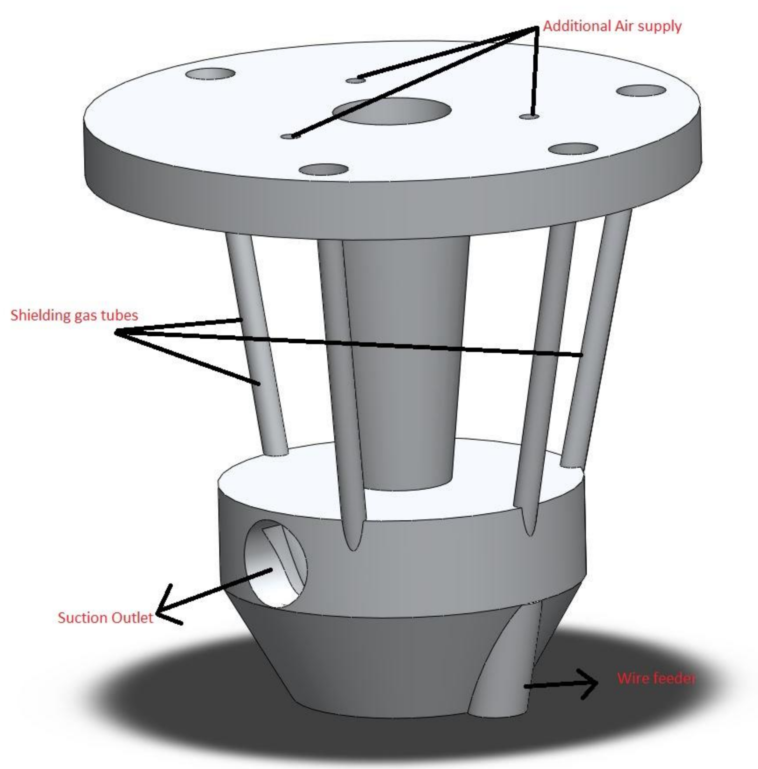


Figure 25: Model view of design 3.0.

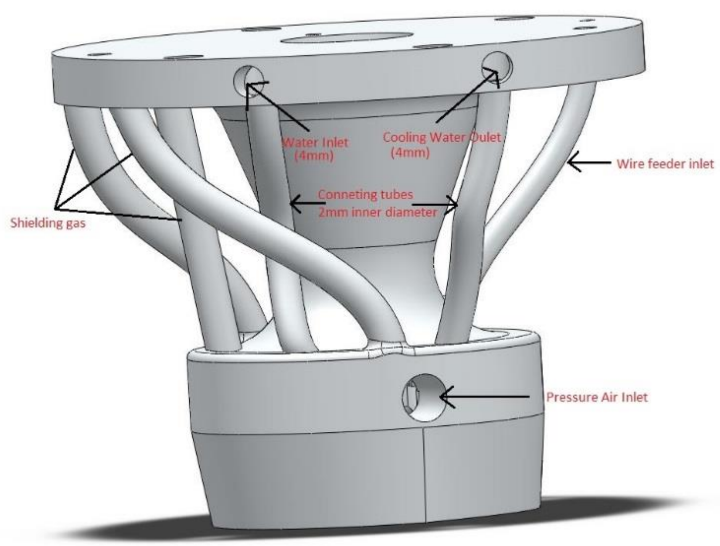
Design 3.0 ensured many features which were required of this nozzle, yet the cooling feature was missing from the current design. Final nozzle was 3D printed with powder bed fusion (PBF) so AM friendly design needed to be considered as well with avoiding possible overhangs and angles greater than 30° to make (citation) them self-supporting features.

3.6 Design 4.0

Keeping in mind with all the drawbacks and requirements from earlier design models, fourth design focused more on making the whole design AM friendly. Cooling of the nozzle base was of another importance to this design as the metal vapor rising from the process can heat the nozzle. Also, minor design modifications were done to make this nozzle better at accumulating most of the smoke for example the oval shaped nozzle base. It resulted in better design for AM manufacturing as well because of self-supporting characteristic of oval shapes. All the details on revised features with this design are presented below.

3.6.1 Effort towards self-supporting AM design

As can be seen from Figure 26, straight tubes feeding wire and shielding gas are replaced with self-supporting tube structures. The base of the nozzle is also modified with curved structure to add support during 3D printing of the part. Some space was also required for water cooling tubes as can be seen in Figure 26 (b). Nozzle base near to the LMD process has also been modified to obtain oval shape which is better than round shape design used in earlier designs during additive manufacturing (Figure 27 (a)).



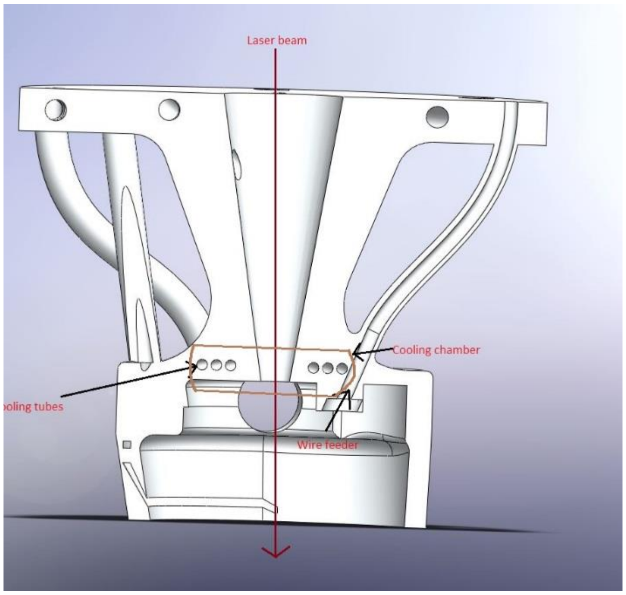


Figure 26: (a) Design 4 model (b) Section view with cooling chamber.

3.6.2 Cooling feature

The proposed nozzle for LMD process operates only 5 mm away from the surface of workpiece itself, hence the heat accumulation in nozzle is inevitable. During initial brainstorming session, use of cooling tubes for nozzle base was discussed and hence this fourth design was focused on integrating this feature. Cooling tubes running around the base of nozzle are of one-millimeter diameter with three spiral tubes around the laser beam opening. Cross section of cooling chamber from top view is illustrated in Figure 27 (b) to show the position and alignment of cooling tubes. Cooling tubes were connected with cold water inlet and outlet openings around the edge of top of the nozzle as seen in Figure 26 (a). Water inlet and outlet connections are made with 4 mm standard connectors with passage sections of 2 mm in the connecting tubes and 1 mm cooling tube diameter.

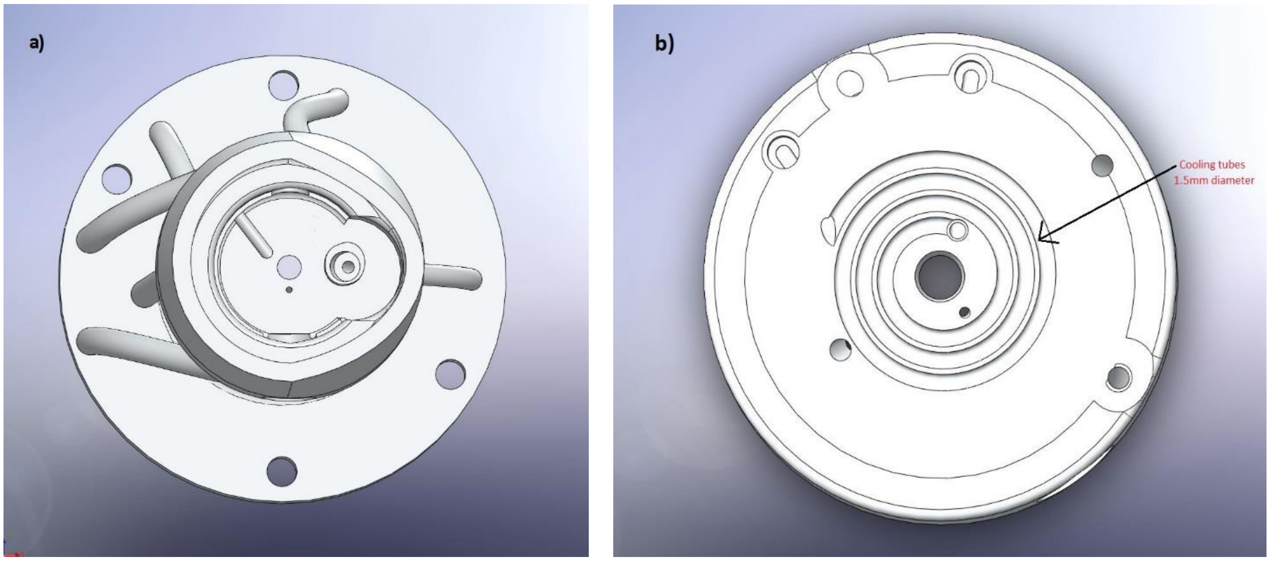


Figure 27: (a) Bottom view of nozzle (left) and (b) cross section view of cooling chamber (right).

3.6.3 Wire Feed Unit

Changes were also made to the location of wire feeder unit in this design. Earlier in design 3.0, wire feed unit was located on the leading edge outside of but adjacent to the main nozzle. However, it raised the problem of angular misalignment of wire fed into the process without changing the size of the whole nozzle during this design. To avoid this problem, wire feeding was designed to take place inside the nozzle passing from the side of cooling tubes and at an angle of α degrees (α=68°) feeding wire exactly into the process from feeder outlet (Figure 28 (a)). Feeder outlet is fixed with wire feed nozzle to assist in this process and the wire feed nozzle is supposed to be changed with every LMD process because of its proximity to the process. Wire is fed constantly through industrial wire feeders kept separately to the nozzle head. Design was carried out to fit in 1 mm of deposition wire into the process.

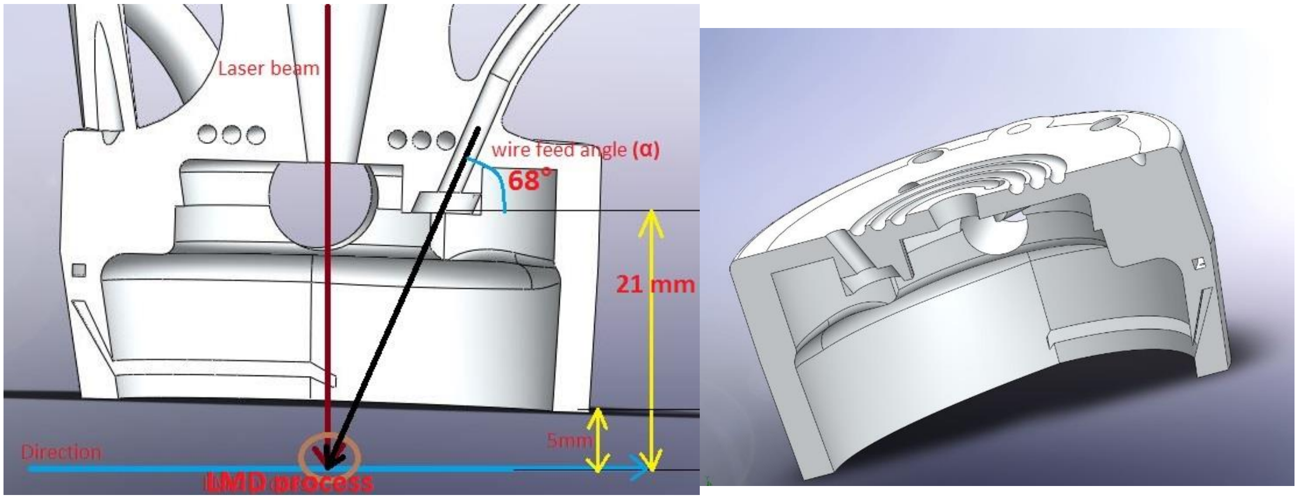


Figure 28: (a) Cross section view of wire feeding position (left) and (b) cooling tubes (right).

3.6.4 Air pressure and suction unit

The first and foremost requirement of this nozzle design was to have external air pressure and suction combination to blow away metal plumes and smoke from LMD process. This specific function was always the focal point during design iteration hence in this design attempts were made to maximize this functionality with few design tweaks. Since wire feeder nozzle outlet was moved inside the proposed nozzle, it was blocking the air flow of pressure air and suction system. Smooth air flow was restored in this section using opening around wire feed nozzle area as it can be seen from Figure 29.

Air inlet opening was of 3 mm outer diameter which was reduced to 2 mm in middle and back to 3 mm in the inside opening to create a local venturi effect thereby increasing the pressure air velocity to carry metal plumes and smoke. On the other hand, suction opening is kept at constant of 8 mm inner and outer diameter as can be seen in Figure 29. This phenomenon takes place 21 mm (Figure 28 (a)) above the LMD process which helps to create localized vacuum in the process area thereby reducing the problem of oxidation during LMD. There will be, however, supply of additional shielding gas to protect the deposited layers from oxidation. The proposed setup was designed to replace the whole cross jet feature used in laser processes to protect laser

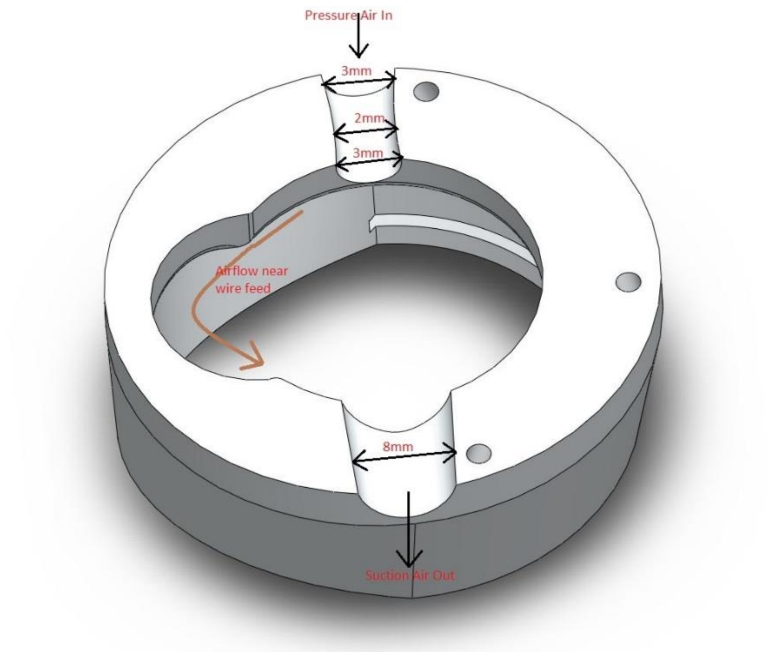


Figure 29: Cross section view of pressure air inlet and suction outlet.

optics from process smoke and make the process area smoke free. The position of nozzle itself near to the LMD process ensured that most of the smoke and plumes get sucked through the suction outlet thereby avoiding the contamination of lens protecting window glass.

3.6.5 External pressure air channel

Additional air supply was improvised in this version with more directed flow towards nozzle end through laser passage hollow area. This was achieved by positioning air channels inclined more towards laser beam passage waist. The number of pressure air channels were also reduced from three in earlier design to two because of its supplementary feature characteristic.

As mentioned earlier, the function of this air pressure was to create a fail-safe smoke free environment for laser optics which lie above the nozzle. During the LMD process, pressure air and suction mechanism is mainly responsible for blowing the smoke away from the nozzle. However, if some smoke were to pass through laser passage waist then suction cannot pull that out. Hence, pushback compressed air supply was made from the top of nozzle directing these possible escaping smoke and plumes back into the smoke chamber. Figure 30 below illustrates this pushback concept applied in the design.

Connection of this additional pressure air is made with regular 3 mm connector and the air composition is not decided in this study. Inert gases which do not interfere the LMD process can be used for this purpose. Detailed connection channel for this pressure air along with other air channel used in this design is discussed later in section 3.6.8.

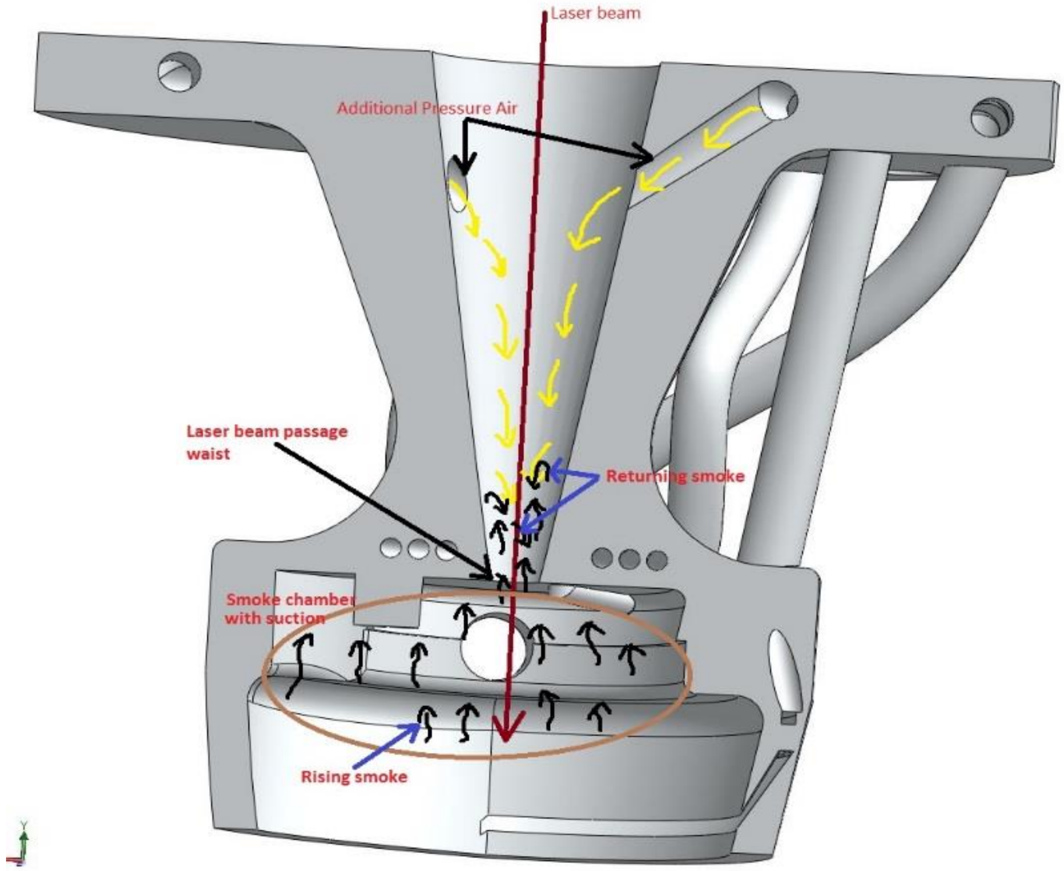


Figure 30: Pictorial representation of working of additional pressure air

3.6.6 Shielding gas flow

Shielding gas used in the process to protect LMD from oxidation was supplied with three tubes as discussed earlier in Design 3.0. However, connection to those tubes were made with single gas connector on the top of nozzle instead of three separate connectors used in earlier design. The position and direction of shielding gas into the process was made more process specific and accurate. Distribution of shielding gas from three channels into semi-circular outlet was made more even to make the flow more uniform throughout the outlet.

As it can been from Figure 31 (right), there were three different connection points for shielding gas in design 3.0. These were replaced with only one connection point and three separate inner channels distributing from the main connection point to feed three tubes in design 4.0. This reduced the use of repeated air connection points, thereby reducing the air leakage possibility and taking full advantage of 3D printing capability with flexible yet complicated inner channels. Inner channel connections are shown in detail later in section 4.6.8.

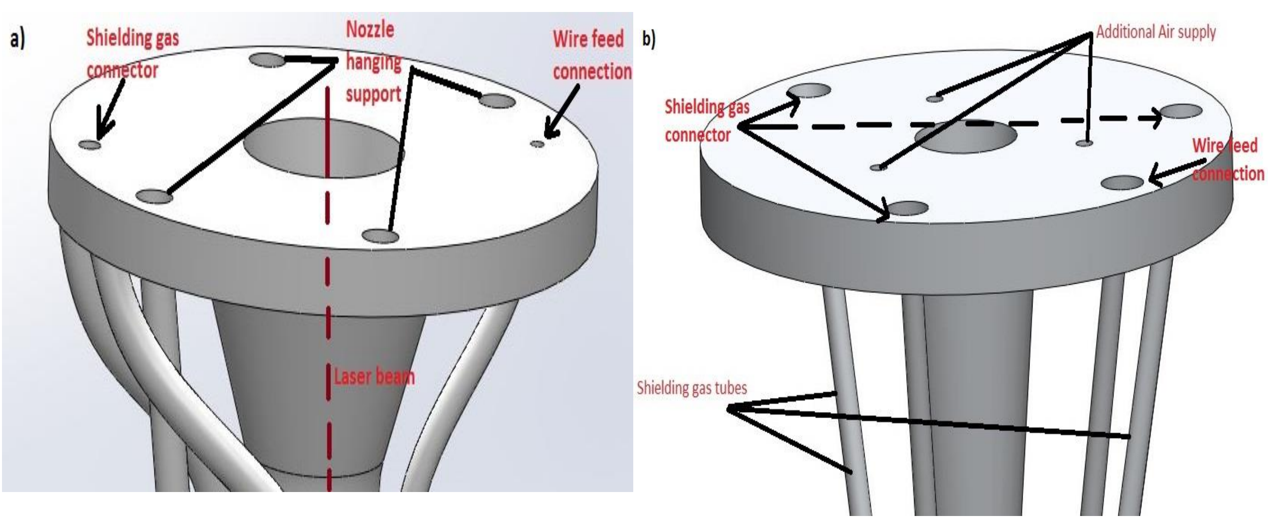


Figure 31: Pictorial representation of working of additional pressure air. Design 4.0 connections (left), Design 3.0 connections (right).

Another major change made to this design was the location and distribution of shielding gas into the process. Earlier, shielding gas outlet was located at the edge of nozzle end with direction angle of 30° (Figure 32 (a)). This setup was good to protect deposited layers from

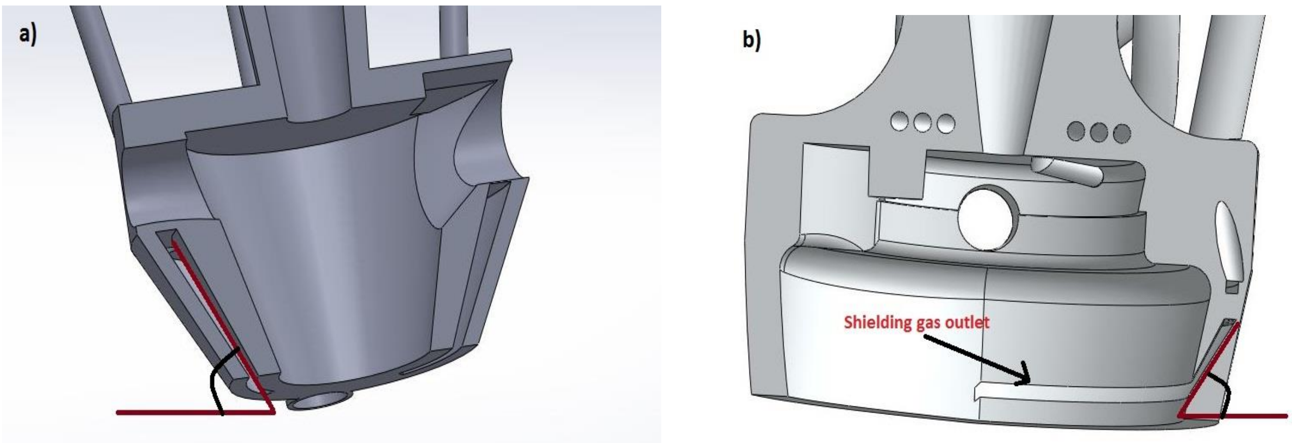


Figure 32: (a) 30° angle of shielding gas in design 3.0 vs (b) 40° angle in design 4.0.

oxidation however, it was unable to shield the process itself with this angle and position as the process was located just 5 mm below the shielding gas outlet opening. This drawback was decided to overcome by placing opening inside the nozzle and with direction angle of 40° towards the process. This ensured that the shielding gas is distributed right into the deposited bead and also supplied into the process. The changes made can be seen in Figure 32.

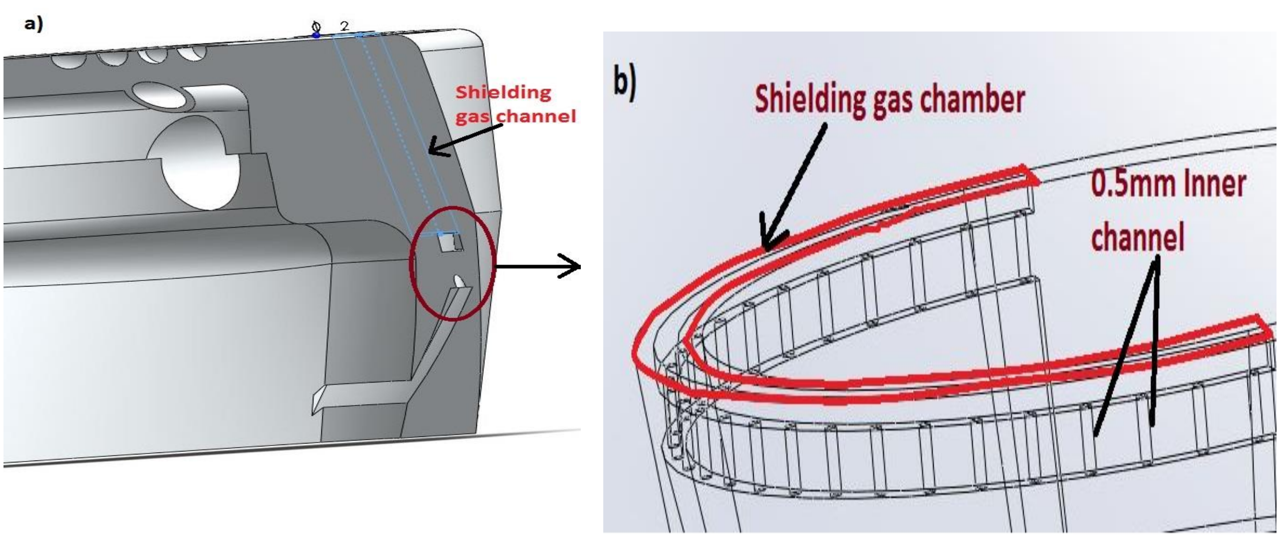


Figure 33: Design for uniform distribution of shielding gas.

Changes were also made to the way how shielding gas passed from three connecting channels to shielding gas outlet chamber to ensure the uniform distribution of gas throughout the opening. A separate shielding gas chamber was created inside the nozzle where gas carried by three connecting tubes were stored and 27 small connecting channels were made to connect this chamber with outlet chamber. The diameter of small connecting inner tubes were 0.5 mm each. This setup was an upgrade to earlier design setup where connecting tubes were fed straight into the opening chamber. Figure 33 illustrates the idea behind this uniform distribution technique used in this design version.

3.6.7 Process monitoring sensor channel

In-situ monitoring is the key to perfect LMD process. Process monitoring with the use of sensors is quite often used during powder LMD process. It results in better deposition profile, hence attempt was made to integrate this feature in wire feed LMD process. Process monitoring sensor channel integrated with nozzle itself gives freedom to add sensors and photodiodes to monitor the wire feed LMD process without the need for external connections for the same function. In this design however, because of lack of space, focus was made to fit in a single photo diode to monitor smoke activity of the process. This setup was helpful for detecting the smoke activity and monitoring the smoke removing efficiency of the nozzle.

Small opening was made near to the laser beam passage waist directly above the process to monitor the smoke activity. Photo diode was fed through top of the nozzle to all the way down of nozzle just above the opening. Assumed dimension for photo diode to be used in this nozzle was of 1.5 mm diameter which was inserted from the top of nozzle and process monitoring hole dimension was of 1 mm diameter. Figure 34 gives pictorial representation of process monitoring sensor window setup. This opening was further supplied with pressure air to push back the rising smoke and plumes into the smoke chamber.

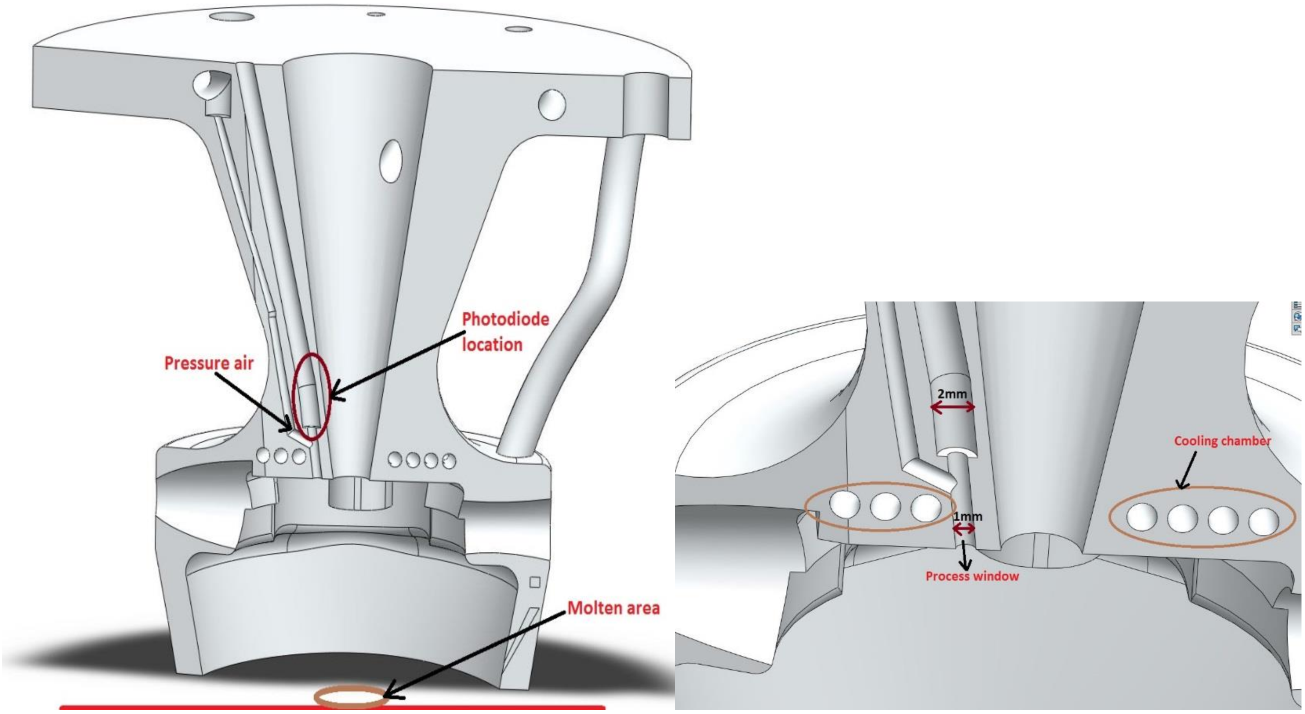


Figure 34: Photo diode tube and location in nozzle (left), process window and tube dimensions (right).

3.6.8 Connecting channels for pressure air and shielding gas

Channels supplying pressure air and shielding gas were optimized with fewer connection ports to reduce possible leakages through these ports and to make the design more rigid with less wire connections. Shielding gas connections were changed from three different individual holes to only one master connection point and inner channels were made to distribute gas into three different carrying tubes. Similar strategy was adopted for channels with additional pressure air. Single input port was made for pressure air distribution around the top of nozzle for fail-safe additional air supply and air supply into process monitoring opening. Figure 35 shows all inner channels made for air supply at the top.

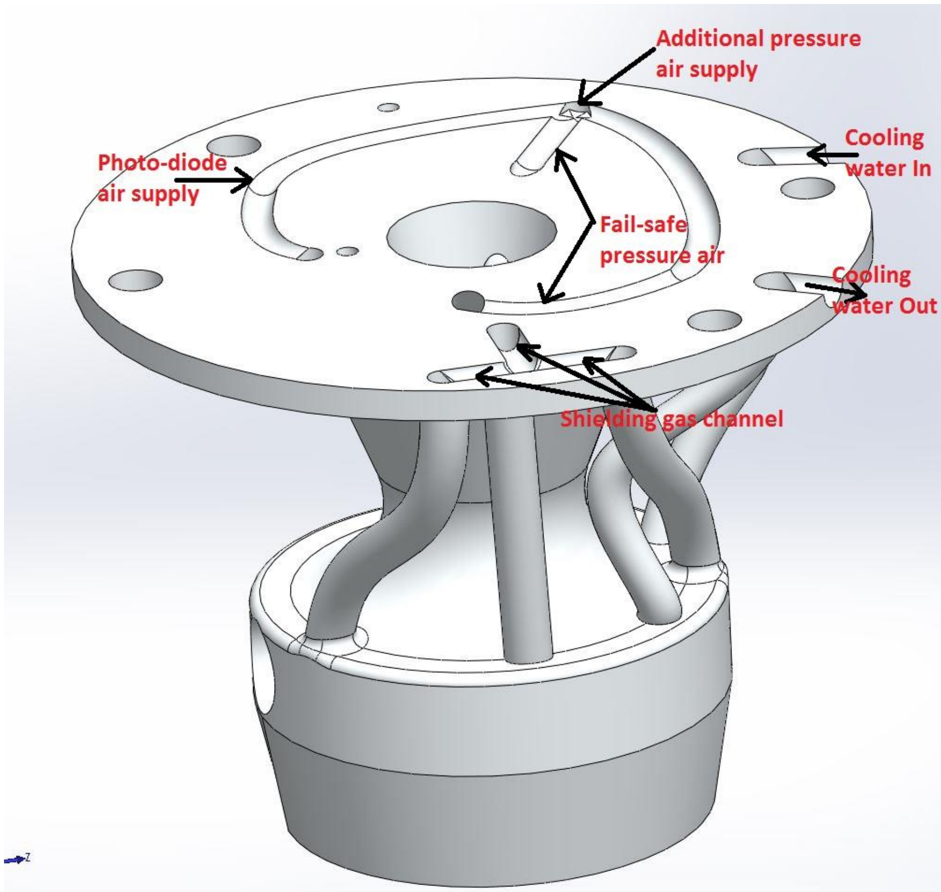


Figure 35: Top plane cross section representing inner tubes for pressure air and shielding gas.

3.6.9 Nozzle arrangement with laser

The nozzle designed above is connected to laser head during the LMD process. This nozzle is designed with concept of connecting it with laser optics using connecting tube in middle. Connecting tube metal has not been selected in this study. Assumed focal length of laser was 155 mm, the height of nozzle is 59 mm and the nozzle standoff distance is 5 mm, which made sense to have 91 mm connecting tube attached with focal lens. Nozzle and connecting tubes can be assembled with regular screws. There are four support screw holes in proposed nozzle and the connecting tube each of 5 mm diameter. Figures 36 and 37 gives better understanding of this set up.

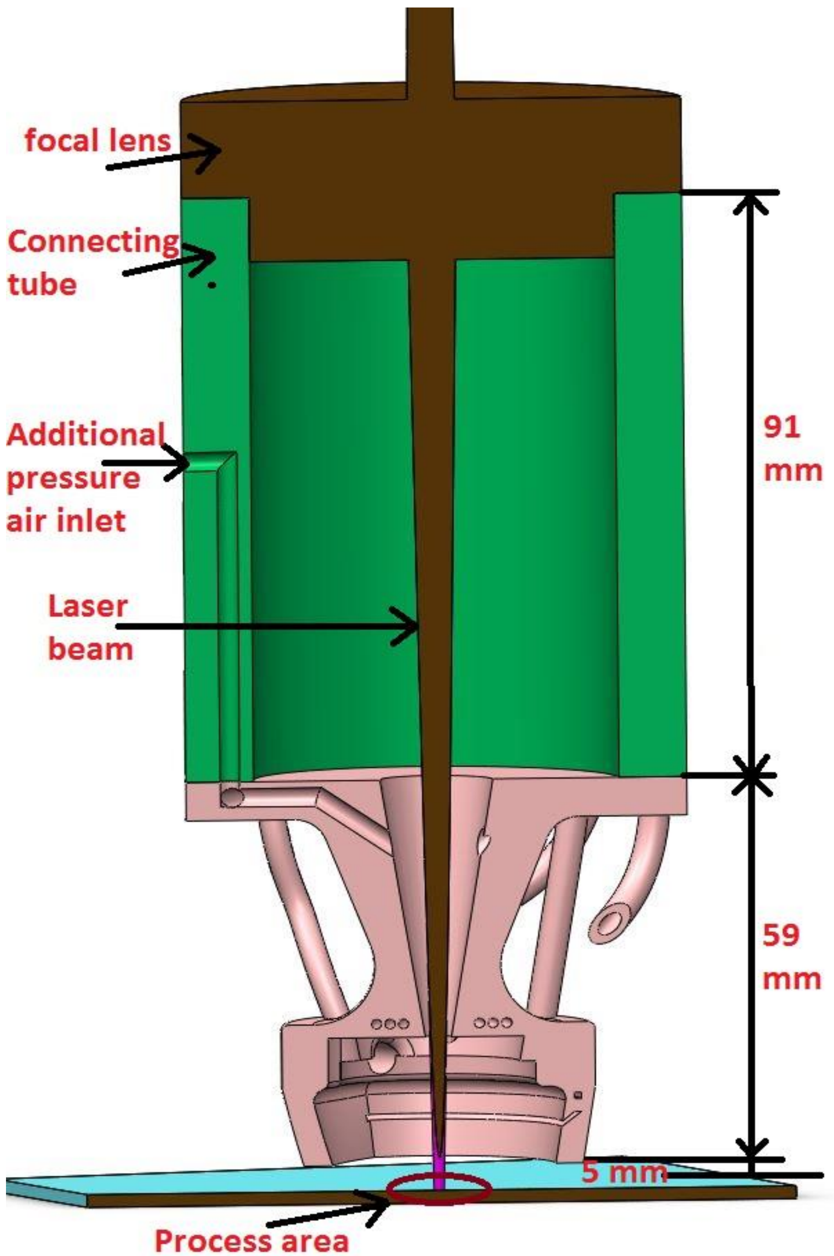


Figure 36: Schematic of nozzle and connecting tube arrangement.

3.6.10 Post processing

As the CAD model was printed with PBF method, final nozzle piece required minor post processing tasks before it could be adjusted to the laser optics head. First of all, all the support structures used during 3D manufacturing should be carefully removed. Metal powder must be brushed off and smooth finish can be achieved with sanding. Tubes and holes could be cleaned with abrasive water cleansing or sand blasting to make sure there are not any blockages. In this nozzle, machining of holes is needed to create screw threads for nozzle support to laser head connecting tube and also to adjust wire feeding nozzle in the wire feeder outlet is needed in post processing.

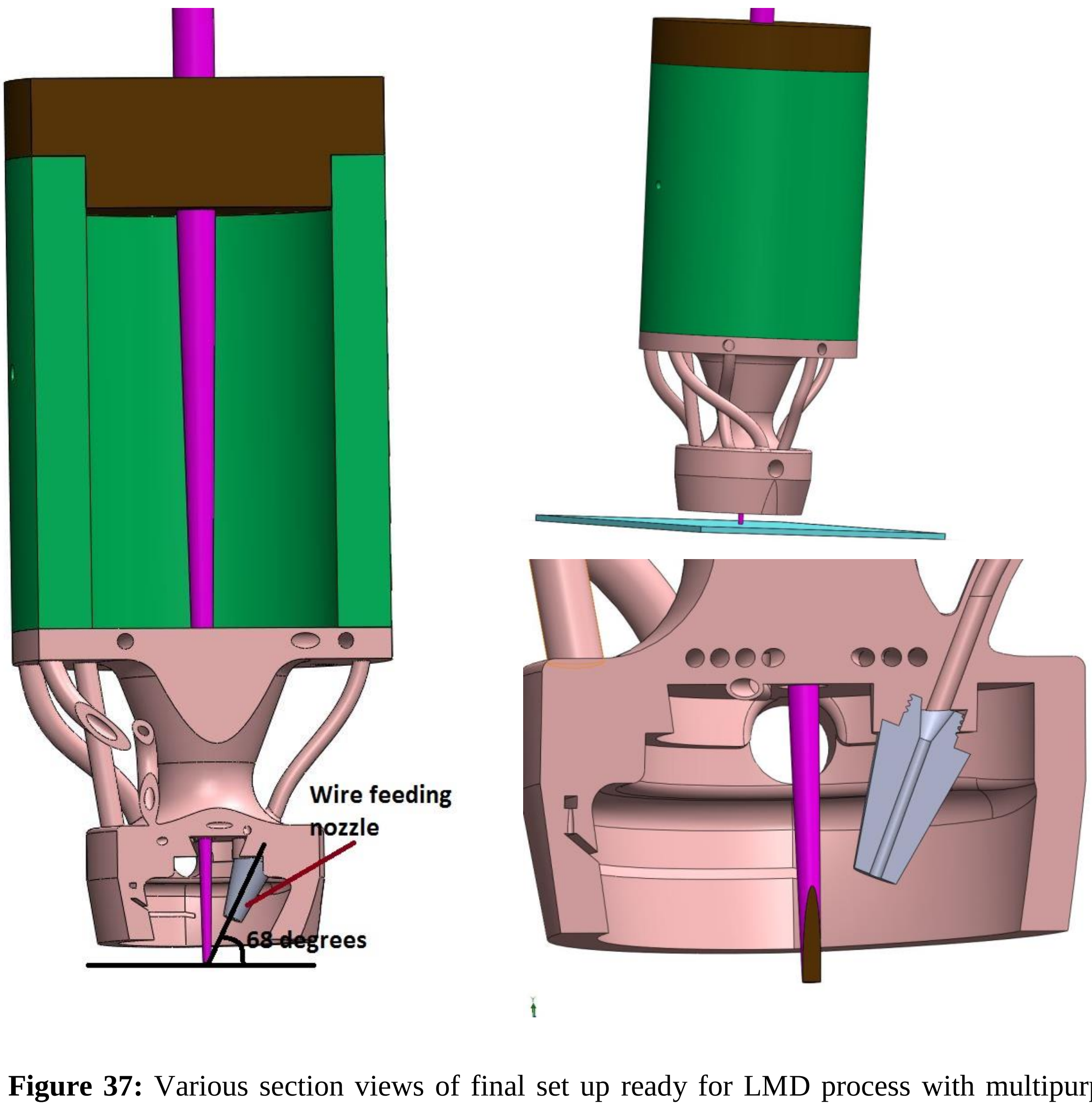


Figure 37: Various section views of final set up ready for LMD process with multipurpose nozzle.

3.7 FDM printed model of Design 4

Final design of the nozzle (Design 4.0) implementing proposed design dimensions was printed by Prenta FDM 3D printer. Pictorial representation of final printed part is shown in Figure 38. Final print was smooth overall but the details were missing since the precision with FDM printer was low with the use of 0.8 mm plastic filler wire diameter.

Figure 38: FDM printed final design of the proposed nozzle

3.8 Critical Dimensions of Proposed Nozzle

Table 6 below represents the general idea about the dimensions used in this design to achieve this wire feed angle, nozzle shape, shielding gas flow, cooling and other features. Corresponding numbers representing the features are shown in Figure 39. This is specifically based on current design and hence will change if design modifications are done in any way. Detailed drawing is attached in Appendix I & II to provide better understanding of the proposed design.

Table 6: Critical dimensions used during nozzle Design 4.0

Number in Figure 39	**Feature**	**Value**
	Height (mm)	59.00
	Upper Width (mm)	74.00
2	Lower width (max) (mm)	25.00
	Standoff distance (mm)	5.00
3	Diameter of wire feeder outlet (mm)	5.00
4	Beam aperture (lowest at waist) (mm)	4.00
5	Shielding gas angle (°)	40
6	Shielding gas distribution tubes (mm)	0.50
7	Shielding gas connecting hole diameter (mm)	3.00
	Shielding gas tube wall thickness (mm)	1.00
	Wire feeding angle (°)	68
	Wire feeding tube wall thickness (mm)	2.00
8	Wire feeding tube hole diameter (mm)	2.00
9	Additional Pressure air inlet hole (mm)	3.00
	Cooling water inlet diameter (mm)	4.00
	Cooling water outlet diameter (mm)	4.00
	Cooling tubes diameter inside nozzle (mm)	1.00
	Pressure air inlet (smoke removal) (mm)	3.00

Table 6 continues: Critical dimensions used during nozzle Design 4.0

Number in Figure 39	**Feature**	**Value**
	Pressure air suction (mm)	7.00
10	Photo diode tube (mm)	2.00
11	Process monitor window (mm)	1.00

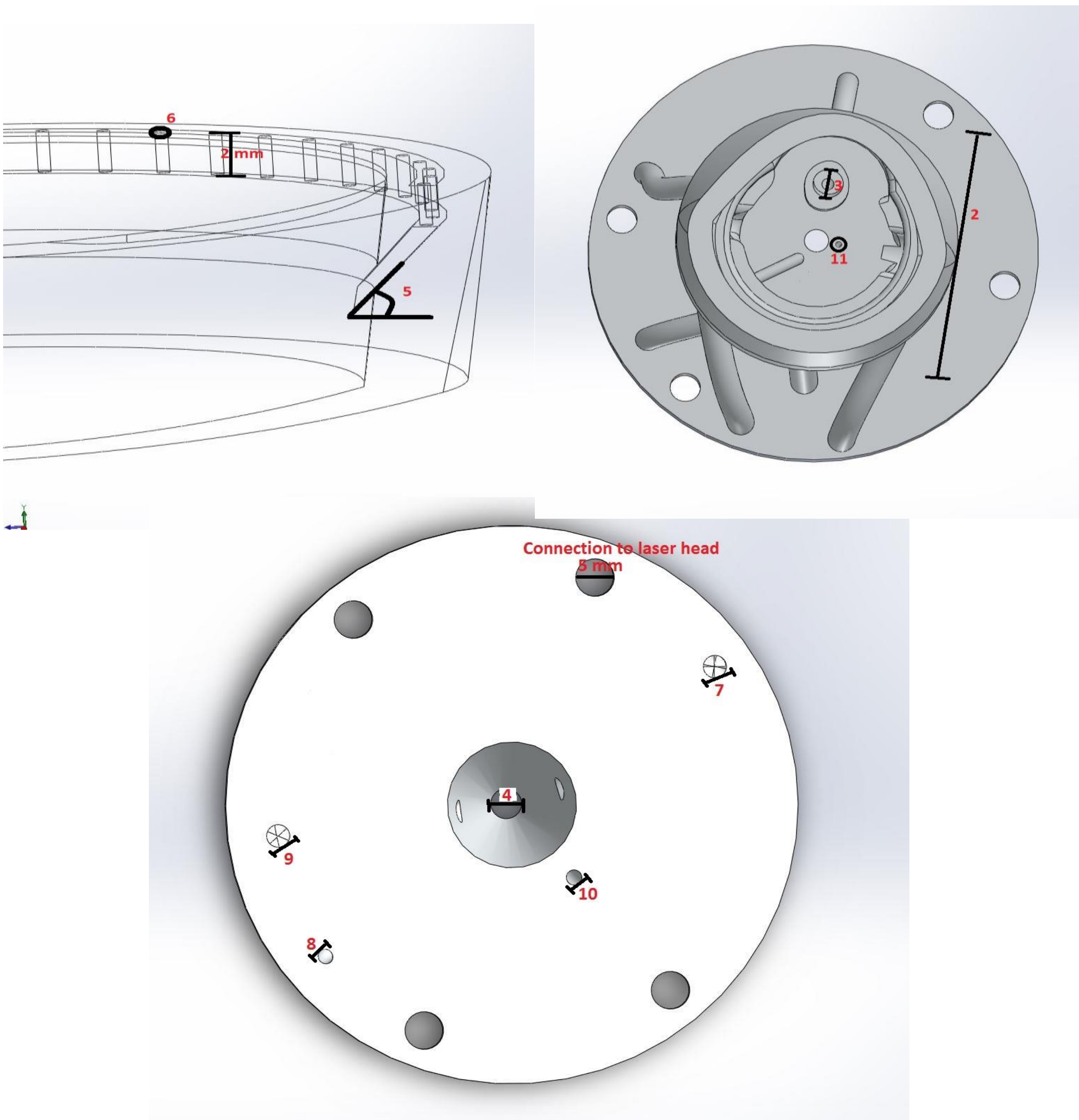


Figure 39: Critical dimensions used in final design illustration.

4 DISCUSSION

Research works carried out in the field of LMD process focus more on powdered LMD than wire feed LMD. Among researches done for wire feed LMD, process parameters and their effects on final structure and micro structure analysis prevail over novel innovations in process optimization such as nozzle design. Present scenario of wire feed LMD has separate individual arrangement for laser beam nozzle, wire feed nozzle, shielding gas supply and cross jet feature. This has led wire feed LMD process to be direction dependent proving it to be a major hindrance towards wider acceptance of the process. Current work, in contrast, was focused on development of single multipurpose nozzle that could allow laser beam passage, shielding gas supply to the process, wire feeding nozzle integration along with cooling feature for nozzle and replacement of cross jet requirement with external air pressure and suction unit. The results show that it is possible to integrate aforementioned functions into a single nozzle which can be assembled with laser head.

Replacement of cross jet feature with pressure air supply and suction technique located in closest proximity to the process was the main idea of this research. Cross jet techniques mostly implemented in laser related applications right above the nozzle and below laser optics blow away process smoke and any dust flying towards optics to keep them contamination free. Even though these are widely accepted techniques, this still leaves metal plumes and smoke near the process because of its location away from the process. Proposed design has improvised additional pressure air supply inlet right above the process at the end of nozzle to blow out rising smoke and other process dust from the nozzle. Integrated suction mechanism was developed along with pressure air for this functionality. Such arrangement resulted in smoke free LMD process and also ensured no contamination for laser optics. Moreover, additional pressure air was supplied from top of the nozzle into the main laser passage opening to create a fail-safe design for smoke free solution during LMD process. This pressure air pushed back remaining rising smoke, if any, back into the smoke chamber which are sucked away with suction system.

The final nozzle designed in this thesis work presented an opportunity for water cooling of nozzle itself. This was an unprecedented feature for a nozzle during LMD process. LMD is a heat intensive process exposing the nozzle constantly to high temperature, smoke and plumes. There was always water-cooling system for laser optics to prevent it from overheating, but water cooling of nozzle was a unique way to make sure that the nozzle had longer lifetime and safer work environment prevailed. Water pumped from the top of the nozzle through inlet opening ran all the way down just above smoke chamber through circular water passing channels to cool off the heated nozzle. Returning hot water got out through separate outlet channel at the top of nozzle. This feature could be added to existing powder feed LMD nozzles and cutting nozzles as well, if needed.

Wire feeding nozzle was of another importance during this nozzle design to make it least direction dependent with higher wire feeding angle resulting in near coaxial wire feeding into the molten pool. Earlier set ups in wire fed LMD process required separate wire feeding nozzle mostly off-axial to the beam axis. This resulted wire fed LMD process being extremely direction dependent – process with leading edge providing better and smoother layers. Even though complete direction independency could not be achieved, final nozzle design however was able to feed wire at 68° angle straight into the melt pool without interaction of beam and wire before the pool. This minimizes the risk of beam reflection phenomenon often prevalent in laser welding and cladding processes.

Shielding gas integration into the nozzle design and uniform distribution of shielding gas supplied with three different supply channels were other challenges. Shielding gas distribution towards the process melt pool area had to be balanced carefully to be directed towards the process and away from the air supply and suction mechanism right above the process. Delicate balance was found with 40° of shielding gas direction angle from gas opening at the lower part of nozzle. Other aspect of shielding gas to be considered was the uniform gas distribution. Three channels carried shielding gas into the gas chamber where it was distributed evenly with 27 different 0.5 mm diameter small tubes and fed into semi-circular shielding gas opening passage. The whole idea was to achieve maximum uniformity in shielding gas distribution and this design helped to achieve that. Shielding gas used for LMD process was independent of this nozzle design as mentioned earlier.

Online process monitoring is an integral part of LMD additive manufacturing which allows smooth and fine manufacturing of layers. During the development phase of the wire feed LMD nozzle, an idea was proposed to integrate process monitoring window in the same nozzle. Photo-diode window was hence added directly above the process to an already multi-purpose design. This allowed to monitor smoke coming out of the process and the smoke suction mechanism effectiveness. Even though this was a primitive process monitoring sensor in the proposed design, it made integration of other in-situ monitoring accessories possible ofr future nozzle versions nevertheless. Process monitoring sensor opening was even ensured to be smoke free with additional air inlet supplied to push back any rising smoke into diode hole.

In addition to all these dynamic features, design-for-use was adopted during the design of this nozzle unlike traditional design approach which use design-for-manufacturability concept. This was achieved with iterative designs with four different nozzle versions modified according to the use required of the nozzle. Additive manufacturing was always the main focus of the design framework which made it possible to design many air and water channels inside the nozzle without any single assembly feature. It would be extremely difficult to manufacture this nozzle had it not been printed with 3D printing. Many inner cuts and narrow sections with free-flowing shapes would have resulted in numerous different parts which would need assembly to bind them together as a single nozzle unit. As this model comes into operation being fully functional, it would inspire other design-for-use applications in future which is a real benefit of additive manufacturing technology. Mass reduction during nozzle design to make it light weight was also much easier with AM prototyping as design modifications could be carried out without major restrictions on design methodologies.

5 CONCLUSION AND FUTURE DEVELOPMENT

As discussed earlier, AM is an innovative technology for building new parts and carrying out repair works. LMD, in more specific way, provides versatile options for metal parts manufacturing with least restriction on part size and faster manufacturing approach. Powder feed and wire feed are two options for LMD with their own share of advantages and disadvantages. While powder feed LMD process have evolved more regarding the widespread use of LMD process because of large number of research ongoing for this process, wire feed LMD is younger technology with limited research and journal articles. Current work gave an opportunity to improvise nozzle used during wire fed LMD process to integrate smoke suction chamber, shielding gas channel and wire feeding nozzle in the same nozzle body.

To achieve these feature accumulations in a single nozzle, four different design versions were developed. Each version was improvised with design-to-use approach to achieve a final version having shielding gas opening directed towards LMD process, wire feed nozzle inside the main nozzle, and pressure air supply and suction feature. The final design proposed integrating the cross-jet feature used in laser applications within the single processing nozzle comprising of wire feed nozzle and shielding gas. The result was smoke free process and less direction dependency for wire feed LMD process. Cooling of nozzle was added to cool off the nozzle base during LMD process and first phase process monitoring photo-diode chamber was added to monitor smoke activity inside smoke chamber. Finally, FDM model of final design was printed which had all required functional openings and chambers. The plan was to 3D print a metal prototype with PBF technique but that could not be achieved because of some technical problems with the university printer. 3D printed prototype is compatible with laser optic head and is ready to be used for metal deposition experiments after required post process machining is done.

The design itself is multipurpose and innovative, overcoming several drawbacks of traditional wire feed LMD nozzle overcame. However, there is still room for further improvement in future. Metallic printed version of final design should first be tested for the real LMD application and modified according to required changes. In-situ process monitoring option has only basic functionality in this design which could be further incorporated with advanced pyrometers and CCD cameras mounted to it. Feedback channels linked to processors can provide real time data during wire feed LMD process. Design modifications could be done to incorporate shielding gas, wire feeding and arc passage area for arc welding nozzle applications as well. Suction and additional air pressure could be increased to get the best results for arc welding applications.

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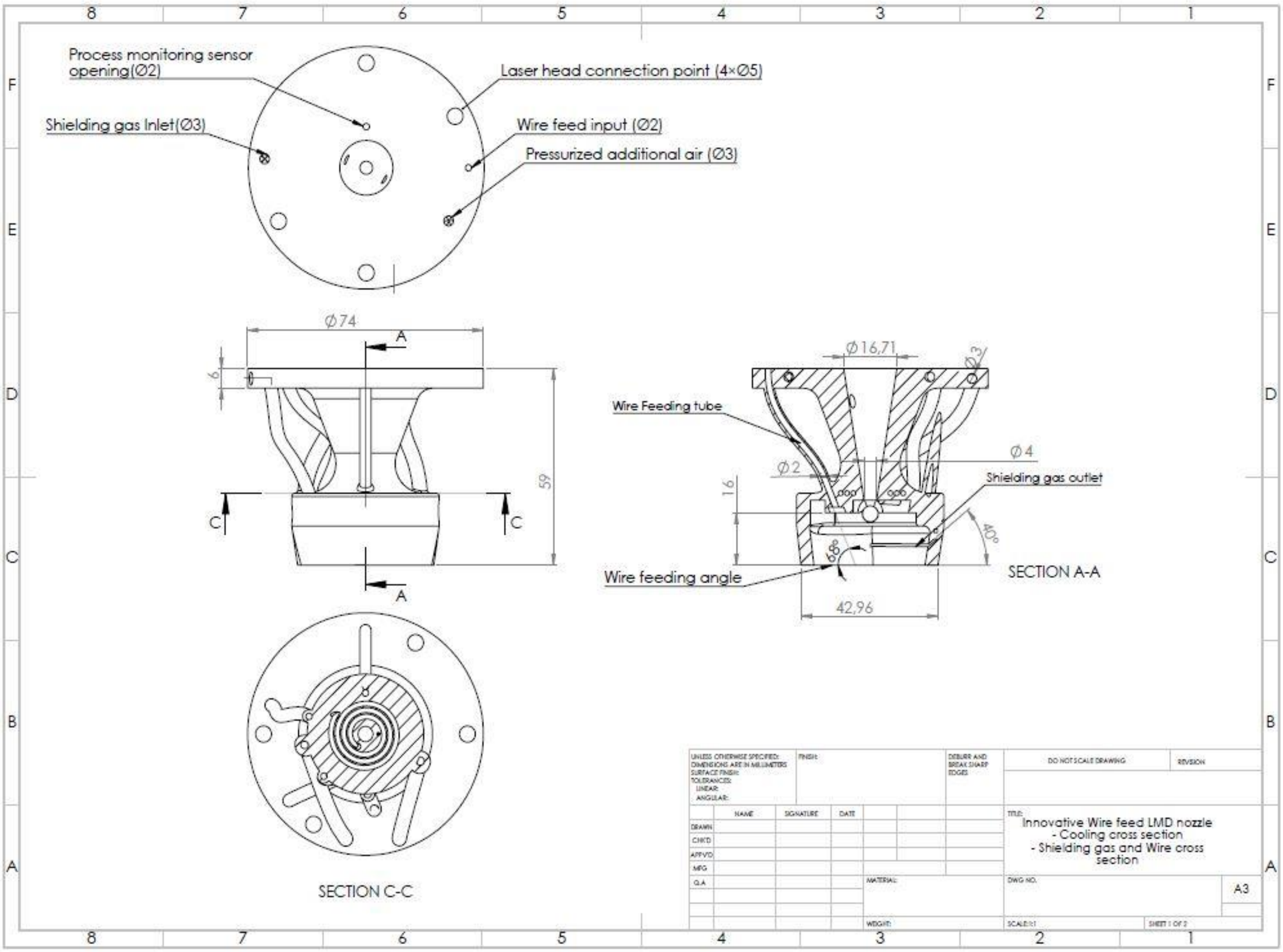
7 APPENDIX

7.1 Appendix I



7.2 Appendix II