LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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A NEW APPROACH FOR DESIGN AND DEVELOPMENT OF A METAL ADDITIVE MANUFACTURING MACHINE

Examiner(s): Professor Antti Salminen
D. Sc. (Tech.) Hamid Roozbahani

ABSTRACT

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This thesis gives a detailed design structure of a new metal additive manufacturing machine which has new processes that are in line with the latest advancement the metal additive manufacturing industry has made. The report has complete details to build the first prototype excluding electrical unit and software functions. The machine is designed exclusively for 316 L stainless steel metallic powder. The thesis briefly explains the main components of the machine that include laser, scanner head, powder feeding, powder removal, gases in the chamber, cylinders, loading and unloading of workpieces. The working of every mechanism and components is also described along with their technical specifications. The machine has 3 mains modules and 1 integrated module built.

The objective of the thesis is to build a machine that is competitively priced in the market with features that speed up the printing and handling process. The design is based on the gap existing in the present metal AM machines and the future opportunities in the market. Selection of components of the machine has been carried out with extensive research and availability in the local Finnish industry first and then extended to the European market. Design for Manufacturing and Assembly approach has been carried out during the entire design process.

The design results shows the efficient approach the machine has towards printing and powder handling process. The results are compared to 2 metal AM machines that are existing in the market. The parameters included for discussion are the building size, the laser power, the powder handling process and the loading and unloading of work specimens. The report concludes the opportunities to grown in the market and further modules that can be added to the machine for post processing applications and the flexibility of machines that can print different metallic powders.

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LIST OF ABBREVIATIONS

3D	3 Dimensional
AC	Alternating current
AM	Additive Manufacturing
CAD	Computer Aided Design
CNC	Computer Numerical Control
DC	Direct Current
DCV	Direction Control Valve
ESA	European Space Agency
FR	Filter, Regulator
GE	General Electric
HEPA	High-Efficiency Particulate Arrestance
ISS	International Space Station
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LSR	Load, Signal, Receiver
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturer
PBF	Powder Bed Fusion
PUN	Polyurethane
PFAN	Perfluoralkoxyalkan
PAN	Polyamide
RM & T	Rapid Manufacturing and Tooling
R&D	Research and Development
STL	STereoLithography

1 INTRODUCTION

The rise of technologies in slicing 3-Dimensional (3D) Computer Aided Design (CAD) models and layer by layer printing has termed 3D Printing or Additive Manufacturing (AM) to be the manufacturing trend of the future. The Powder Bed Fusion (PBF) process, which is a technology of melting layer over layer using laser has advantages over the traditional manufacturing process for example die casting, in which the manufacturing costs increases with the complexity of shape of the product and escalates with the decrease in lot sizes of the product. (Poprawe et al. 2015, p. 50.)

Rapid Manufacturing and tooling (RM & T) have benefited from the growth of AM. The costs incurred in creating tools and templates for molding and casting is lower when compared to traditional means of manufacturing. Using AM technologies it cost about \$1,000 whereas using traditional means it cost about \$300,000. The post processing costs are also reduced and this has driven many industries like aerospace, motor sports, architecture and consumer product industries to turn to AM for RM & T. (Chua & Leong 2015, p. 491.)

However, there has been challenges in regarding to AM with the limited number of parts that can be built during a single print. The volume of parts produced in the traditional milling or casting process is higher than the parts that are printed. Companies have begun investing in larger building platforms, multiple scanner head, tandem lasers, higher laser power and scan speed to overcome these barriers. (Poprawe et al. 2015. p. 51.) The quality of finished products made from investment casting or Computer Numerical Control (CNC) milling is higher than AM products. The rise in technology have brought printed metals to the quality of sand casting. (Chua et al. 2015, p. 491.)

The current trend of metal 3D printers have seen benefits in complex design capabilities, reduction in time for lead parts, increase of efficiency in manufacturing and quality of products being high. The efficiency of the manufacturing increases and there is a shorter time required to reach the market. (Stratsys 2015, p. 10.)

These factors on a conclusion basis proves that the metal additive manufacturing process will keep growing and technologies will enable these systems to give accurate and faster finished products.

1.1 Background of the metal AM markets

The 3D printing market is forecasted to reach $7.3 billion in the year 2016. The markets have burst open and the existing players are developing the machines rapidly. The biggest player in the Original Equipment Manufacturer (OEM) markets have been Airbus and General Electric (GE) Aviation that have custom built metal AM machines. GE has spent about $50 million in building a production plant that makes 40,000 fuel nozzles using meal AM. (Wohlers & Caffrey 2015, p. 74.)

The aerospace industry is the top manufacturing hub that relies on metal AM due to the complex shapes of products, lower number of units and scope for redesign. The European Space Agency (ESA) has planned to deliver a metal AM machine at the International Space Station (ISS). The bigger space agencies like National Aeronautics and Space Administration (NASA), China Aerospace Science and ESA have been conducting Research and Development (R&D) to print metal in space. (Wohlers et al. 2015, p. 76.)

Siemens have decided to invest a €21.4 million in Sweden on a metal AM machine. Companies are playing big from their pockets and have the desire to invest on the metal AM machines. The fuel nozzles produced by the GE facility have already begun installment into the engines this year. (Wohlers et al. 2016, p. 46.)

Until the year 2015, the biggest existing companies that have ventured into the 3D metal printer markets have been 3D systems, EOS, Concept Laser, Phenix systems, Arcam, Optomec, Solidicia and SLM solutions (Chua et al 2015. p. 490). Japan, USA, China, South Korea, France and Norway have invested in the metal AM markets and have built printers in the year 2016 (Wohlers et al. 2016, p. 48).

1.2 Gap in the industry

Though there have been a growth of metal AM machines in the market, there is a gap in the features these machines have to offer. The cost of a metal AM machines are close to

$658,000 million for a size of 550 x 550 x 500 mm (Wohlers et al. 2016, p. 47). The existing machines have followed just the standard method of loading new plates for building, removal of the part piece and then post processing.

1.3 Goals

The goal of the paper is to have a metal AM machine that is efficient in the design and is advanced in technology than the other metal AM machines in the market. The machine should have proper materials for the components that are used in building the machine, suitable mechanism to attain higher accuracies, higher laser power and larger focal diameter to speed up the melting process. The machine is built with the aim that there is going to be minimal engagement between the operator and the machine. The ergonomics and safety of the operator is an important factor for the design keeping in mind the least minimal engagement.

Finally for the metal AM machine to compete in the market the pricing strategy of the machine should be competitive as all segments of manufacturing industries must be reached. This can be achieved by using optimal components and parameters for the entire machine. The limitations of the design is the electrical unit, control unit and interface unit however they are explained minimally.

1.3.1 Research questions

The research question is, why the metal AM machine is lacking in efficient technologies for printing metal products in rapid speed, as their productions are slower than the traditional manufacturing process. This paper will answer the problem by using novel design approach for the powder removal process and loading – unloading process of workpieces.

In addition to that, the pricing strategy of the existing machines is quite high for all segments of the industries. The bigger OEM’s like Airbus and GE can invest in the expensive machines but small industries are going to be the market for future metal AM machines. The design approach will answer this issue by setting up a competitive price and make the machine affordable across all industries.

1.4 Research methods

The research methods that are going to be carried out in this work is comparing the existing metal AM machines available in the market and listing the gaps found in the machines. The defects in the existing machine will give rise to the scope of better and efficient designs in the new model. The comparison of other metal machine manufacturers with the new machine is also carried out. Figure 1 describes the research methodology used in this research design.

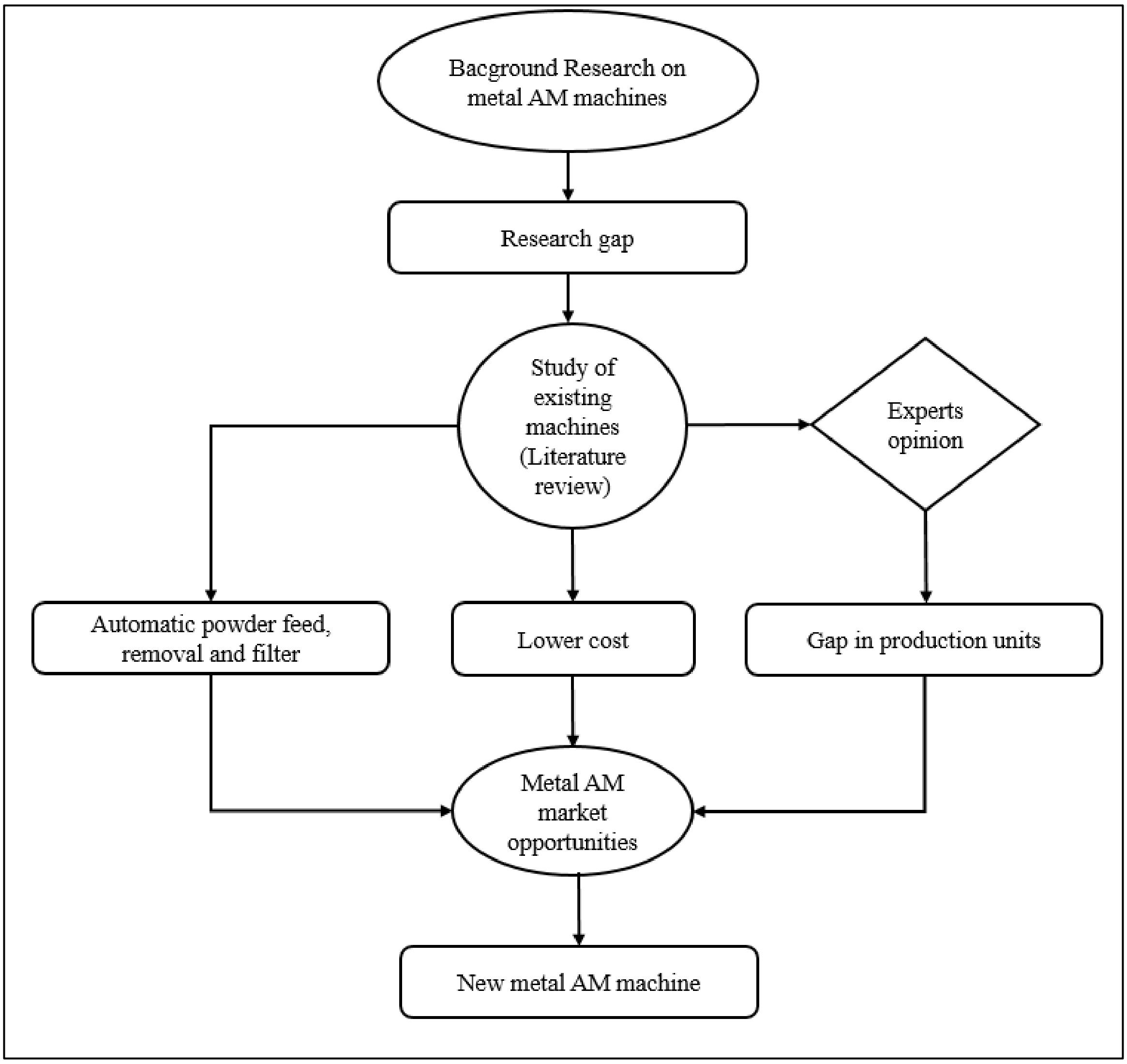

Figure 1. Research methodology flowchart.

2 THE METAL AM MACHINE: OVERVIEW

The machine is developed with new concepts and ideas and haven't used any existing machine as reference base models. The exact dimensions of the machine is 5250 mm x 3185 mm x 2580 mm (Length x Height x Width). It has 3 main modules with one additional module in the rear side. Below figure 2 shows the overall design of the machine. The machine is equipped to melt only 316L stainless steel powder particles.

Figure 2. The machine showing different units a) The powder and filter unit b) The central unit c) Laser and control unit.

The machine consists of the three main units and one modular unit. The powder and filter unit has the new innovation for powder feeding process and filtering it when the one build is completed. The recycling of the powder is unique in its innovation as the production unit does not undergo any hitches and workpieces can be manufactured continuously.

The central unit is divided into 2 main sections. The top section is the main building chamber and it is carried out in nitrogen atmosphere. The nitrogen generator and circulation unit built within the machine is a breakthrough of having a compact metal AM machine.

Once the workpiece is finished it is brought to the lower section. In other words the melting process is carried out and eventually the workpiece is brought down from where the workpiece is removed. The powder reservoirs have a volume of 0.1 m^3. The building platform can build workpieces to the size of 400 mm x 400 mm x 400 mm (Length x Height x Width) which is big volume in this range of metal AM machines. The platform is able to hold workpieces of up to 1000 kg.

The machine uses a single 500 watt laser and a single scanner head with additional focussing unit vario Scan. The laser used is a continuous wave laser from IPG (YLR – 400 – AC). The laser unit is air cooled and it is placed inside the machine cabinets and primarily on the right side (laser and control unit). The software used to control is an open source software which can be altered and modified for the user.

The exchange or modular unit is a new innovation that has been added to the machine that makes production lines faster and easier. The loading and unloading of building plates along or without the workpieces is carried out by this unit. The removal of workpieces from the built chamber is carried out in such a way that they are free from the powder particles. The post processing work lead time is now reduced and new parts can be automatically printed as the old part is removed. Figure 3 shows the rear module for exchange of platform and workpieces.

Figure 3. The modular unit place on the rear side.

The existing machines or players in the market competing with similar price and technologies have been SLM 500 from SLM solutions and EOS M 400 – 4 from EOS. The below table 1 shows the comparisons of the two machines along with the new machine.

Table 1. Comparisons between 3 machines SLM 500, EOS M 400 - 4 and the new machine (mod. EOS 2016; SLM solutions 2016).

	SLM 500	EOS M 400 - 4	Built Machine
Build volume	500 mm x 280 mm x 365 mm	400 mm x 400 m x 400 mm	400 mm x 400 m x 400 mm
Laser type	IPG fiber laser, 2 x 400 watt	Yb – Fiber laser, 4 x 400 watt	IPG Fiber laser 500 watt
Scan speed	Up to 10 m/s	Up to 7,0 m/s	Up to 7,0 m/s
Overall size	5200 mm x 2800 mm x 2700 mm	4,181 mm x 1,613 mm x 2,355 mm	5250 mm x 3185 mm x 2580 mm
Inert gas	Argon – external supply	External supply of Nitrogen	Inbuilt Nitrogen generator for the process
Powder removal	Automated but requires an additional unit	Manual	Fully automated and is present in the modular units
Part removal	Additional part removal station	Manual	Powder is sucked out and part is removed and new plates are loaded using small conveyors
Price range	Over $1,000,000	Over $1,000,000	Approx. $800,000

The comparison of the machines depicts few advantages in the newly built machine. They are,

- The in-built continuous powder feeder system comprised of powder removal and filtration unit

- The automatic part removal process that includes loading and unloading of finished building plates (with workpiece) and new building plates
- The integrated Nitrogen supply and filter unit
- The competitive price strategy in the market.

However the speed of production units when compared with the existing machines SLM 500 and EOS M 400 – 4 cannot be defined because of the use of multiple lasers and multiple scanner heads.

3 THE CENTRAL UNIT

This is the biggest and the integral part of the machine. It is divided into 2 sections. The top chamber is the building chamber and the lower section is the built chamber. The top section consists of the building platform, the printing chamber, powder feeder and recoater blade units. Whereas the lower unit consists of powder outlet and part removal units.

The two sections are fit against each other using dowel construction and screws. These chambers are air tight and sealing is used to make sure that there is no loss of Nitrogen gas to the atmosphere from any of the numerous outlets. This is a compact unit and outer covers are built using sheet metals and the inner plates are made up of 316L stainless steel.

3.1 Printing chamber

The overall size of the printing chamber is 1700mm x 1200mm x 800 mm (Length x Width x Breadth). The printing chamber has gearbox, the powder feeder, bearings, recoater blade and top door. The temperature maintained inside the chamber is close to 80°C. The pre heating of the chamber is required to have a consistent melting of powder particles by the laser. Figure 4 shows the different components present in the printing chamber.

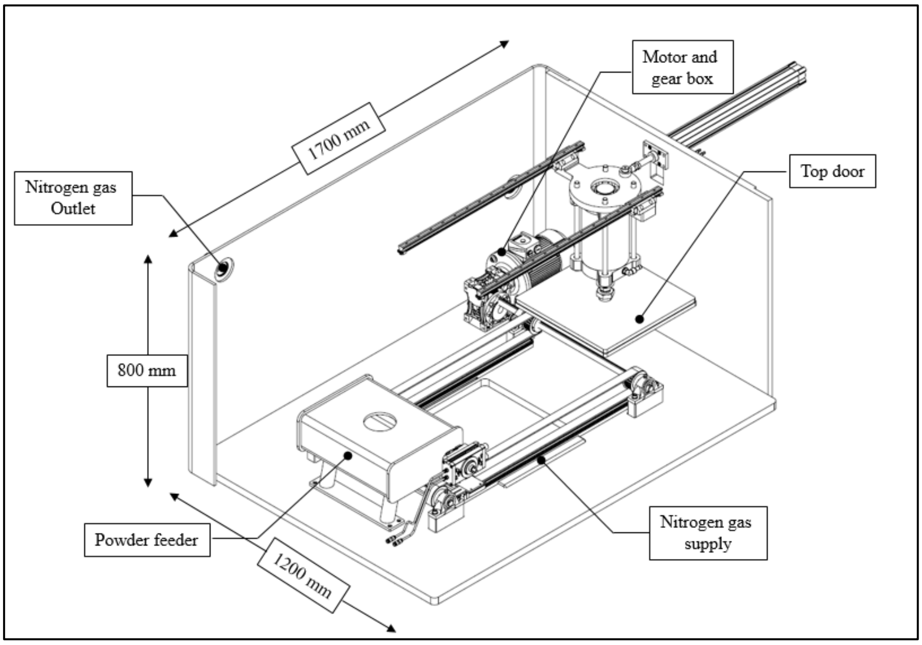

Figure 4. Printing chamber.

The chamber has inlets close to the building platform for nitrogen gas. This is needed for the building platform. The pre heating of the chamber is provided with the heating coils places under the building platform. There are nitrogen gas outlets on the rear side of the printing chamber. These are primarily for the circulation of nitrogen gas inside the chamber.

3.1.1 Bearing housing

The shafts are mounted on to the bearings and they are aligned using key slots. There are 2 shafts in total which are different in lengths. The shafts are hot rolled shafts that have straightness tolerances of -0.01” to 0.01” and diametrical tolerance of -0.0002” to 0”. They are made of 316L stainless steel and cut to length (645 mm and 775 mm) and have a diameter of 25 mm.

There are 4 plummer blocks placed at an offset from the base to intentionally allow the flow of nitrogen gas into the building area. They are corrosion resistant. The key slots holds the plummer block and prevents the shafts from turning independently on its own. The plummer block has a screw that holds the shaft on to the bearing in a rigid manner.

The bearings present in the plummer block are used here are made up of 316L stainless steel and they are ultra-high corrosion resistant. They are able to withstand temperatures up to 140°C without losing their property and function. They are able to withstand temperatures up to 140°C without losing their property and function. Below figure 5 shows the installation of shaft and the plummer block using keyway. (McMaster-Carr 2015a, p. 1212.)

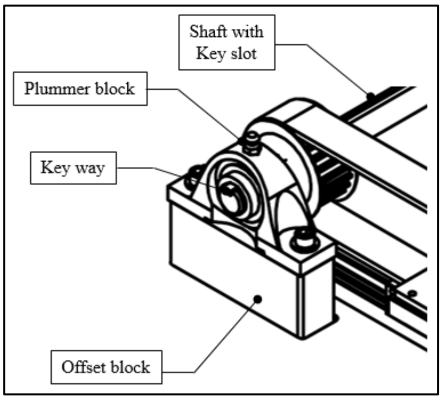

Figure 5. Installed shaft and plummer block (McMaster-Carr 2015a, p. 1212).

3.1.2 Belt and Timing belt pulley

The shaft is connected to the timing belt pulleys or wheel which in turn is connected to the motor unit along with the gear box. There are 4 pulley, 2 on each end of the building chamber. The pulley is made of stainless steel and highly corrosion resistant and the teeth is wedge shaped which is good for the belt. These pulleys are machined and the bore diameter of ∅ 25 mm is machined to h7 press fit tolerance. Figure 6 shows the installed level of timing belt pulley and belt. (McMaster-Carr 2015b, p. 1101.)

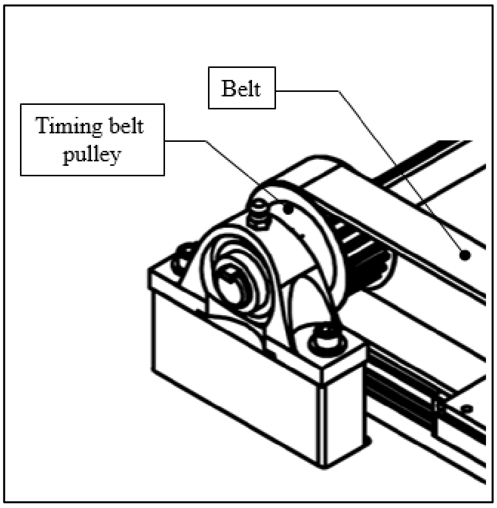

Figure 6. Installed timing belt pulley and belt (McMaster-Carr 2015b, p. 1101).

The shaft is assembled into the pulley using taper bushings. These taper bushings are used to maintain proper fit and alignment between the shafts at both the ends. The straightness is maintained so that there is no slack in the belt. The slack might create a low tension and on the longer run the belt tends to become loose. Below figure 7 shows the timing belt pulley and the taper lock bushing.

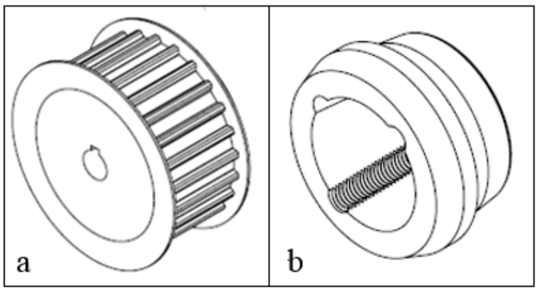

Figure 7. a) Timing belt pulley (McMaster-Carr 2015c, p. 1109) & b) Taper lock bushing (McMaster-Carr 2015d, p. 1092).

The belt is directly assembled onto the timing belt pulley. The trapezoidal teeth belts are made up of silicon and reinforced with Kevlar material. This gives the belt high strength, low tension and good shock resistance which can operate at temperature ranging from -4°C to 200°C. (McMaster-Carr 2015b, p. 1101.)

3.1.3 Rails and motor unit

The rails and motor unit carries the recoater blade from one end of the building platform to the other. The rails have optional bellows that are installed on them to keep them free from the powder particles. The rails are mounted on to the building platform using socket headed cap screws and both the rails are made parallel to each other. Figure 8 shows the linear rails and runner blocks where the recoater blade is mounted

The rails are 956 mm long that covers the whole length for the recoater blade to travel. The rails installed in the machine are from Rexroth Bosch group. The linear rails contain cover strips that makes for a secure mounting and saves time and money for all the holes in the rails. They are made of corrosion resistant steel according to European standards. The surface is smooth to have a sliding effect for the balls from the runner blocks. (Bosch Rexroth AG 2014, p. 7.)

The runner blocks come along with the rails from the sane Rexroth Bosch group. They are ball guided runner blocks and are capable of taking heavy and consistent loads. The runner block is made up of aluminum which is lighter in weight and reduces the weight from steel blocks up to 60%. These blocks require minimal lubrication. The blocks are interchangeable and any fault in the existing block and be replaced immediately without any complications. The noise levels are quite low and hence provide the best travel performance. The figure 8 below shows the model of the runner blocks. (Bosch Rexroth AG 2014, p. 7.)

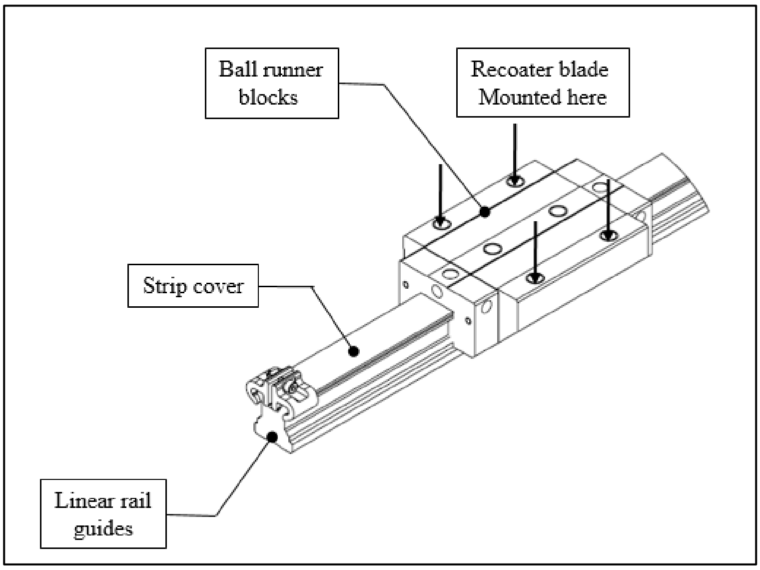

Figure 8. Linear rails and ball runner blocks (Bosch Rexroth AG 2014, p. 7).

The motor unit is the principal component which drives the gear box which in turn rotates the shaft which is mounted on to the timing pulley. The motor is an asynchronous electrical motor that has a frequency invertor. The frequency inverter controls the speed of the motor and this used to control the speed of the recoater blade over the building platform. Figure 9 shows the Motor unit and gear box assembled using screws. In the building chamber it is covered by sheet metal cover to keep it free from powder particles and heat resistant.

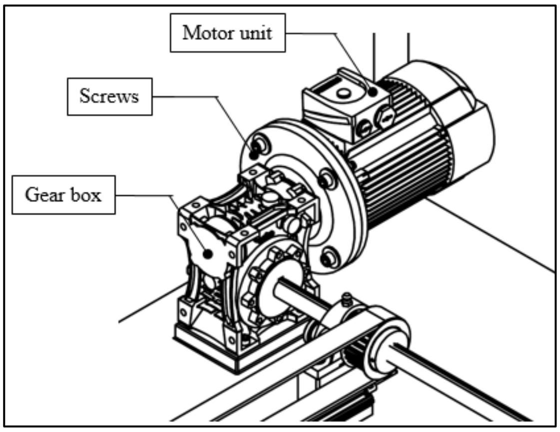

Figure 9. Motor and gear box unit assembled (VEM Motors Finland 2012, p. 5).

3.1.4 Powder feeder

The powder feeder is a reservoir of powder particles inside the building chamber. The powder chamber is able to hold 176 x 10 mm^3 of powder particles. The powder feeder drops the powder particles into the recoater blade. As the depletion of the powder begins new amount of powder is pumped into the powder feeder chamber using the powder pump. The powder pump is assembled on to the powder feeder chamber. The inner dimensions of the powder feeder chamber are 435 mm x 325 mm x 125 mm (Length x Width x Height). Figure 10 shows the overall construction of the powder feeder.

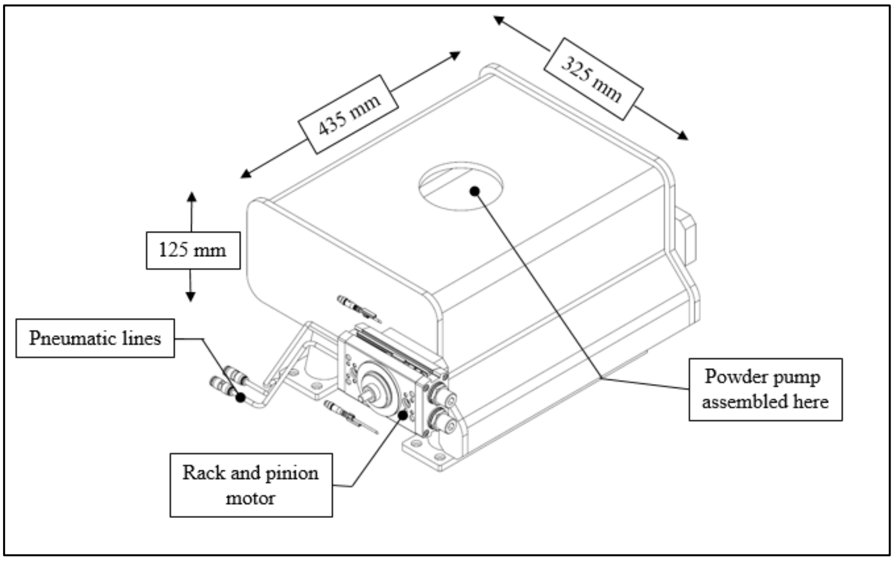

Figure 10. Powder feeder and main components (mod. Festo 2017b, p. 1).

The powder feeder consist of a small cylinder which is attached to the rack and pinion motor. The rack and pinion motor drives the cylinder to +180°C and -180°C. The main purpose of the cylinder is to control the flow of the amount of powder that flows into the recoater blade. The cylinder contains groove cuts that hold just the certain amount of powder and drop it into the recoater blade for 2 coats of powder.

The recoater blade finishes 2 coats and then the powder is filled again from the powder. This process monitors the amount of powder that falls into the recoater blade and it also ensures there is no excess powder. This aims at keeping the powder chamber from not having bulk amounts of powder and there is no floating powder particles. Below figure 11 shows a cross section of the powder feeder and the concept behind the powder feeder.

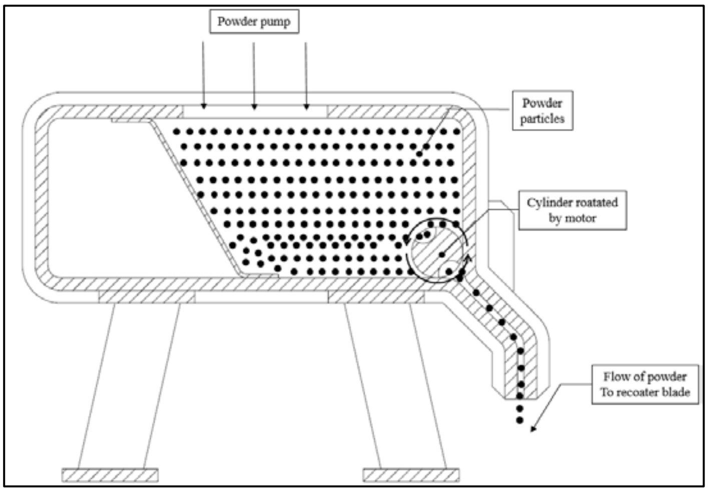

Figure 11. Process of the powder feed chamber.

3.1.5 Recoater blade

The recoater blade is one of the main components in the powder chamber. It carried a pre-determined amount of powder and lays layer over layer powder on the building platform. The recoater blade contains two ceramic plates that are place on the ends of the recoater blade assembly. The ceramic blades are made to be triangular so that the life of the ceramic blades can be longer by using all the three edges.

The two blades present also makes sure that there is no extra powder outside the building platform. The powder is always kept within the walls of the recoater blade assembly. The ceramic blades are held down using screws. Since the ceramic blade is a serviceable component, the screws can be removed anytime and the side of the ceramic blade can be changed. The recoater blade assembly consists of two flanged edges that can be used to assemble on the runner blocks. They are also in turn attached on to the timing belt using socket head cap screws. The powder blade travels with the belt. The figure below 12 depicts the construction of re coater blade assembly.

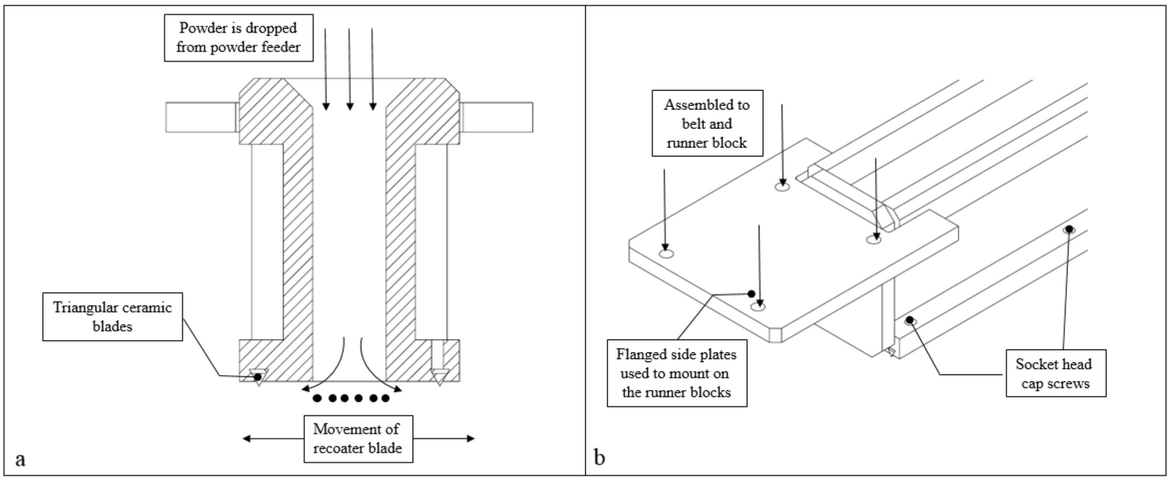

Figure 12. a) Recoater blade cross section b) Isometric partial view.

3.1.6 Top Door

The top door of the printing chamber consists of two pneumatic cylinders. The horizontal cylinder for the linear movement over the rails and the vertical cylinder that holds down the plate at the rod end of the cylinder and closes the chamber. The function of the door is to seal the built chamber with the powder and the workpiece once the printing process is finished. The entire assembly runs over rails that are placed on the top portion of the printing chamber. The rails are from Rexroth Bosch group and have the same runner as used for the recoater blade. The below figure 13 shows the top door assembly.

The horizontal cylinder is a festo double acting cylinder and has a piston diameter of 50 mm. The piston rod end contains male thread and hence this can be attached with screws to push the vertical cylinder on the rails. It has pneumatic connections of G ¼ and the piston rod is made up of alloy steel. (Festo 2016l, p. 1.)

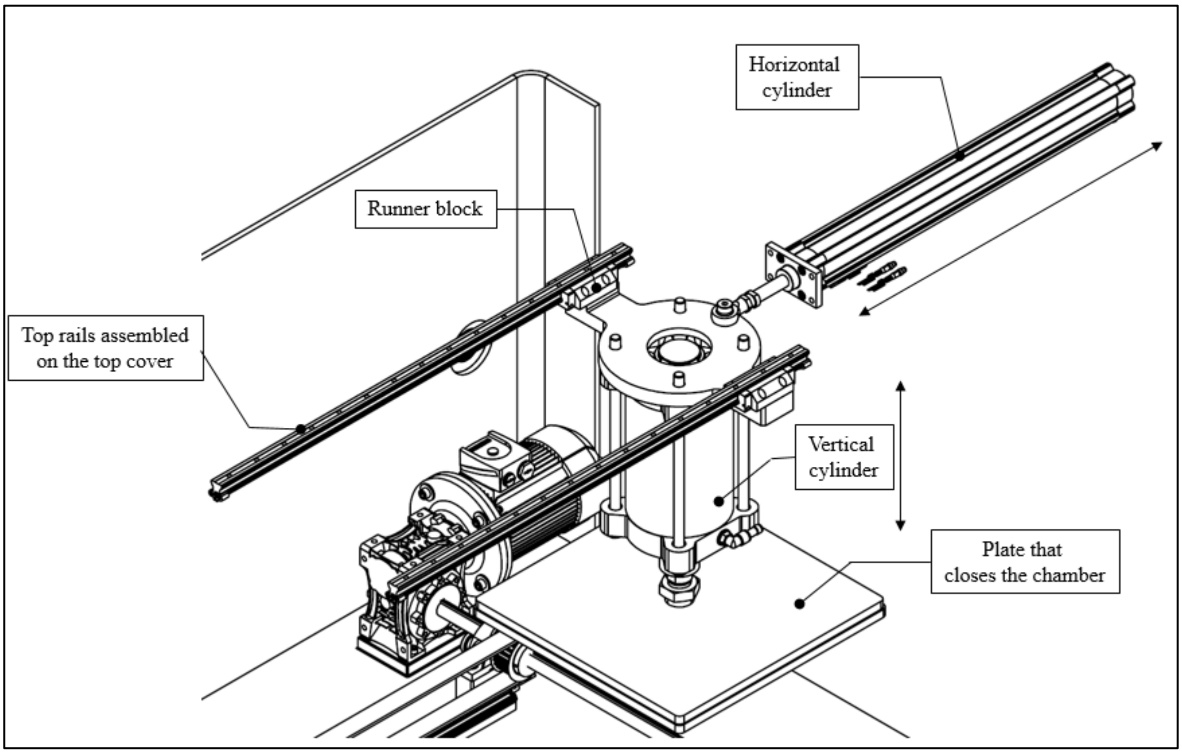

Figure 13. Top door assembly and directional movement (mod. Festo 2016n. p. 1; Festo 2016l. p. 1).

The vertical cylinder is also from festo and has a stroke length of 1 – 2700 mm. The piston has a diameter of ∅ 160 mm and can move weight up to 4 kg. The cylinder is a double acting cylinder and has G ¾ connections. The working temperature of the piston rod is from -20°C to 150°C. The piston rod end is threaded and this is attached to the plate by nuts. (Festo 2016n, p. 1.)

The plate attached to the piston rod end has a rubber sealing around the edges to prevent any leakage of powder back into the chamber. The pressure in the built chamber tends to push the plate upwards. This is prevented by the vertical cylinder keeping the chamber free from small metallic particles. This ensures that there is no need of cleaning the chamber manually unlike the existing machines where the remaining powder is vacuumed out.

3.2 Printed chamber

The printed chamber comprises of the lower section of the central unit. This section has to main parts i.e. the outer boundary that carries the filtration unit and the blower for the powder feeder and it contains the main printed chamber which is the inner enclosure. The inner enclosure is discussed in this section. The filtration and blower unit will be discussed along with nitrogen circulation components and powder feeder components respectively.

The part as it is printed layer by layer is brought down by an electrical cylinder. Once the printing completion is over the top door closes the chamber and the completed part is taken out. The printed chamber is tightly sealed not to allow leakage of any powder particles. It contains inlet for air flow that blows the powder out during the powder removal process. When the air is blown into the chamber there is a vacuum created and then the powder is sucked out through the powder removal outlet. The built chamber contains the opening door to the retraction unit. Below is figure 14 that gives an overview of the printed chamber (inner enclosure) and surrounding components.

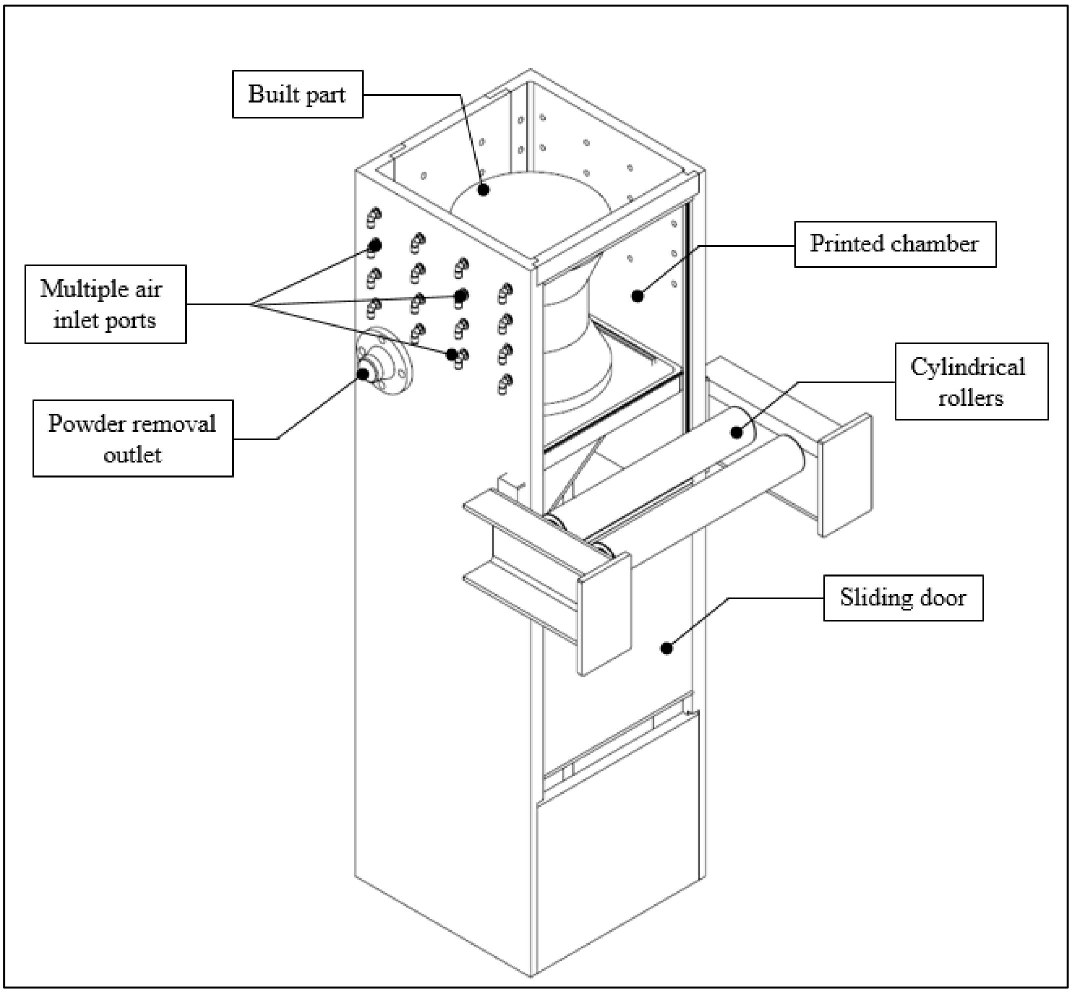

Figure 14. Printed chamber.

3.2.1 Electro Mechanical cylinder

The electro mechanical cylinder is attached to the building platform which lowers it down by 20 -100 microns depending on the parameters that are used for printing. The rotary motion from the electrical motor is converted to linear motion using ball screws. The transmission unit from the motor into the linear shaft is carried out by belts and pulleys. The load pin at the top of the electrical cylinder can hold a maximum weight of 50,000 N. The operating temperatures of the cylinder ranges from -20°C to + 60°C. (Bosch Rexroth AG 2016, p. 17.)

The platform is in turn attached onto Rexroth rails and runner blocks that enables a smooth transition and gives an extra advantage for the weight created by the printed part and powder. This is the part of the machine where high loading stress occurs. The load at fracture is 300% of measuring range. Below figure 15 shows the electro mechanical cylinder in installed position. (Bosch Rexroth AG 2016, p. 17.)

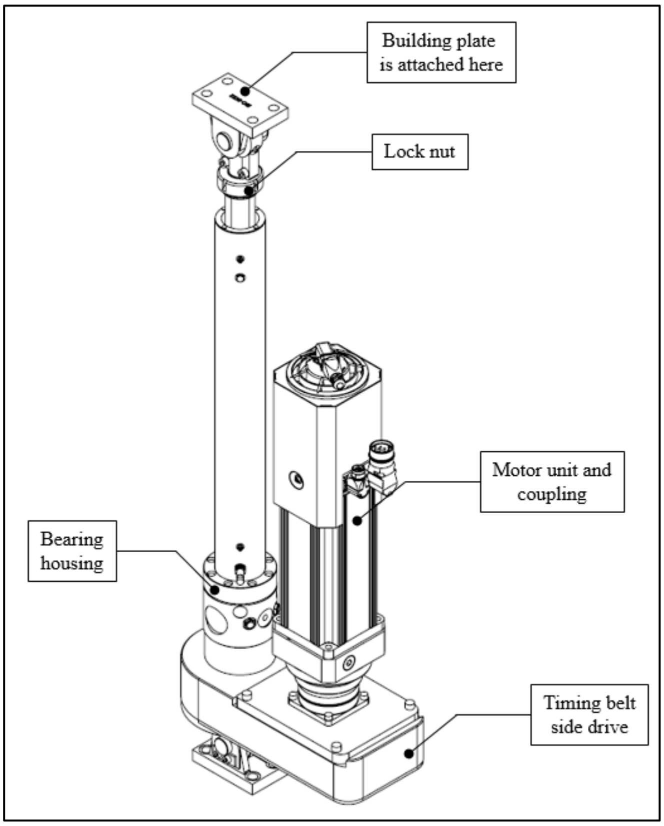

Figure 15. Electro Mechanical cylinder (Bosch Rexroth AG 2016, p. 7).

3.2.2 Building platform

The building platform is attached to the electromechanical cylinder and is moved gradually down as layers of the metal powder are printed. Once the metallic part is printed completely (maximum size 400 mm in height) the workpiece reaches the built chamber. The building platform has a completely new design. The size of the building platform is 475 mm x 475 mm x 50 mm (Length x Breadth x Height). The building plate is in the size of 450 mm x 450 mm x 15 mm (Length x Breadth x Height). The building plate is the new for every different work process. Both the building platform and the building plate are made up of 316L stainless steel.

The building platform has slot cut out where roller bearings are assembled onto it. These roller bearings is used to remove the platform out by the retraction unit. The building platform is lowered to the end of the built chamber. At the end of the built chamber are present two pins. These pins push the building plate at an offset. This makes sure that the building plate is removed with ease along with the finished work piece. The figure 16 shows the building platform and the function of the pins.

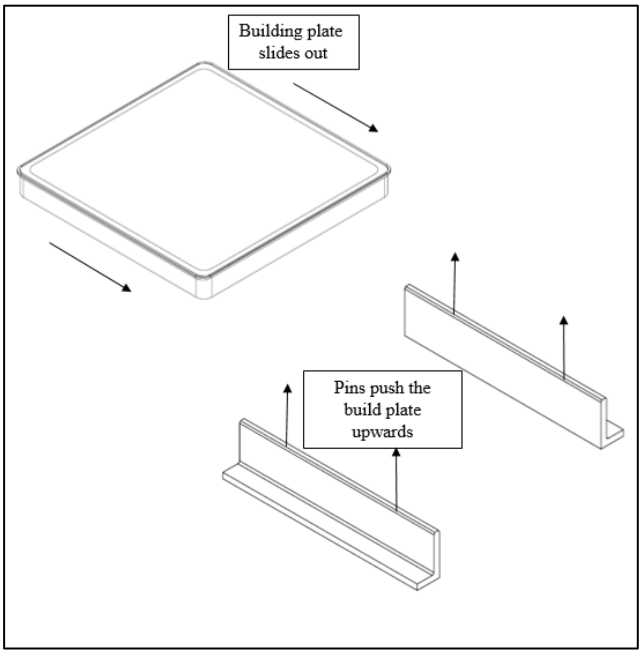

Figure 16. Building platform and pins.

The building platform contains round grooves that are installed with electrical coils. These coils is used to heat up the building platform before the printing process begins. It can heat up to 700°C. The building platform heat slowly passes the heat on to the building plate. The building plate is also in slight contact with the heating coils. The temperature to be maintained in the printing chamber is about 80°C. The ends of the heating coil is connected with a ceramic unit which is in turn connected to electrical wires. The figure 17 shows the assembly of the platform and coils. (Hotset 2015.)

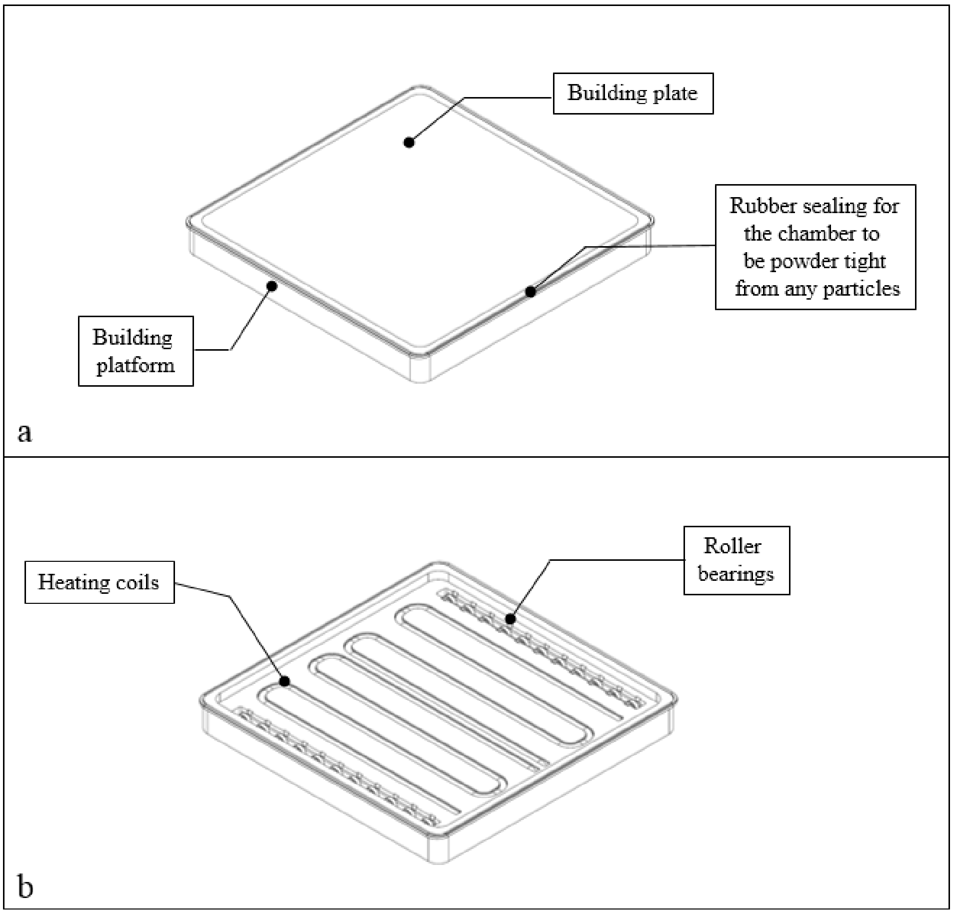

Figure 17. a) Building platform with rubber sealant and build plate and b) Heating coils with roller bearings (mod. Hotset 2015).

3.2.3 Platform Assembly

The platform assembly comprises the building platform, the electro mechanical cylinder, the lifting pins along with rails and runner blocks. The electro mechanical cylinder is assembled directly to the building platfrom using socket head cap screws. The building platform have tubular structures that are used to give additional strength to the electro mechanical cylinder and weight is distributed uniformly. The tubular structures are attached to the runner with the screws. There are two types of runners in this rail. On the left side is present the standard runner used in the building platform. The right side contains runner with sensor unit. The sensor unit is used to achieve the desired height. The figure 18 shows the platform assembly.

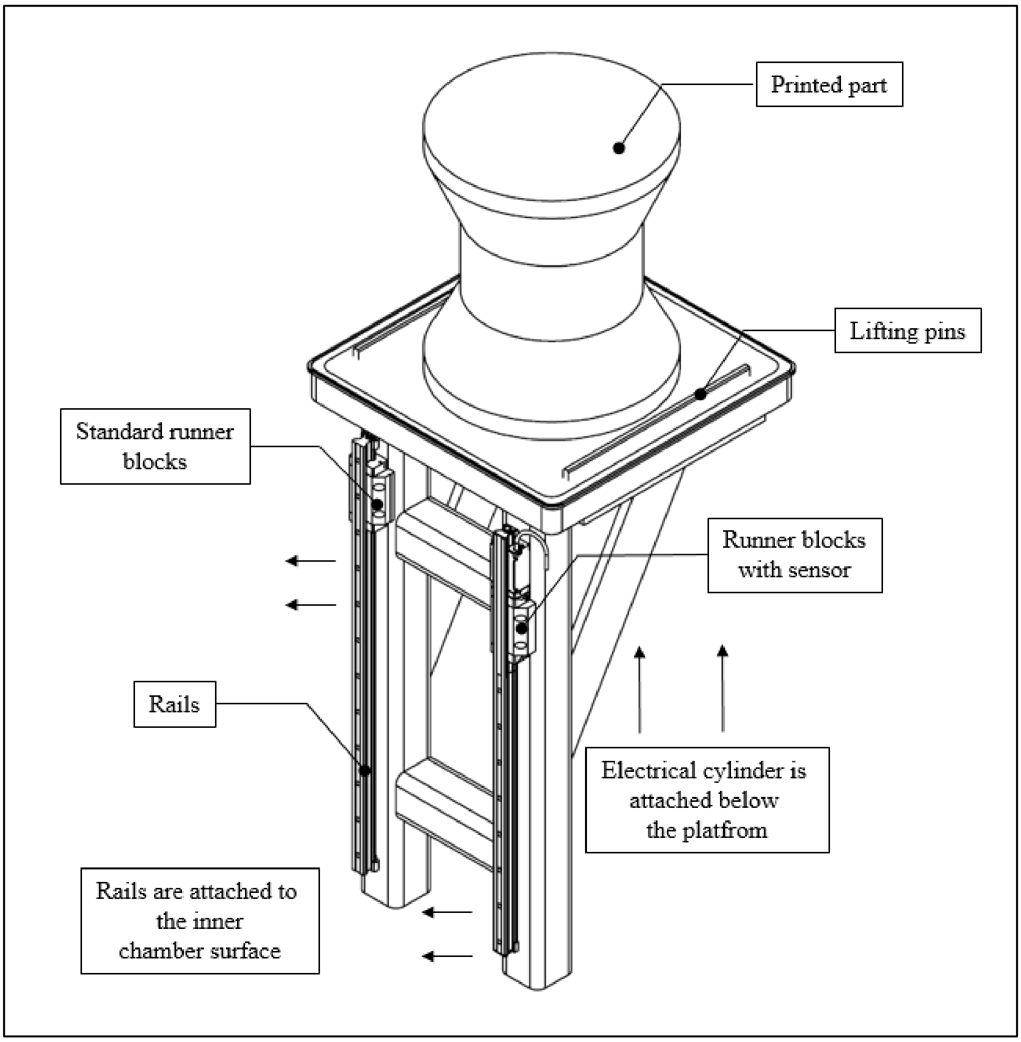

Figure 18. Platform assembly with rails.

The initial height adjustment occurs when the new building plate is loaded on to the platform and lifted by the cylinder to the printing chamber. It is critical for the building platform and the plate in the printing chamber to remain in the same line. This is ensured by the rail sensor. Inaccuracies in the level of building platform and the plate in the printing chamber can cause the misalignment of the recoater blade. The latter height adjustment occurs when the finished workpiece is brought down and the building platform touches the lifting pins.

3.2.4 Chamber door

The chamber door is made up of stainless steel and contains rubber sealant attached to its ends. The rubber sealants does not allow the powder particles to escape out. It ensures the chamber is a powder tight area. As the particles are light they can travel and cause damages to the other machine components. On the sides of the chamber door, there are 4 miniature ball transfers attached. They are threaded and can be screwed into the side of the chamber door. These ball transfers supports the chamber door to slide in the grooves present on the side walls of the built chamber.

The miniature ball is 0.25 inch in diameter and is made up of stainless steel with an aluminum housing. They are highly corrosion resistant and provides smooth transition upwards in a clean environment. The threaded length is up to 0.25 and has a M3 thread. The below figure 19 shows the chamber door and the miniature ball housing assembled on its side. (McMaster-Carr 2015e, p. 1311.)

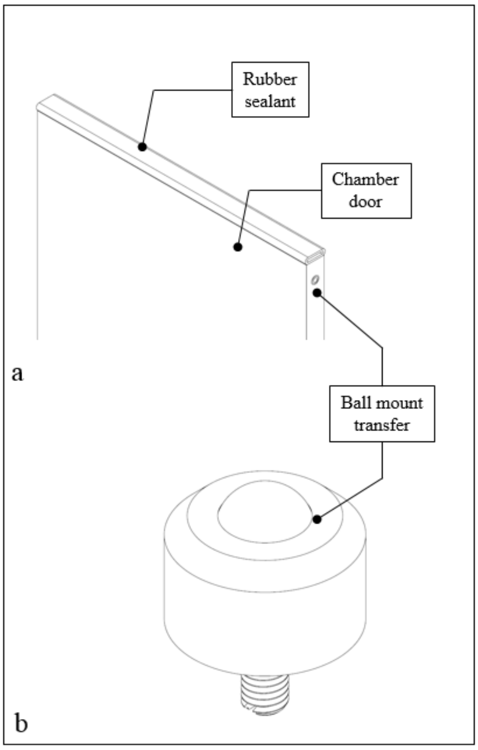

Figure 19. a) Chamber door & b) Miniature ball mount transfer (McMaster-Carr 2015e, p. 1311).

There is a double acting pneumatic cylinder that is attached to the chamber door. The lower or base mount is attached to the stationary plate of the built chamber and the piston head or moving unit it attached to the chamber door. The pneumatic cylinder ensures that there is a sliding motion of the chamber door. When the workpiece is completed the chamber door moves down to let the building plate and workpiece be taken out by the retraction unit, and once the new building plate is loaded the pneumatic cylinder ensures that the chamber door is closed. Figure 20 shows the complete assembly of the chamber door and installation.

The pneumatic cylinder from Festo is a double acting cylinder and has a stroke length from 1 mm – 2800 mm. The cylinder has a push force ranging from 415 N to 7363 N. It has cushion effect at both the ends. It also contains position sensors that makes it effective in this machine. The cushion effects enables the cylinder to automatically adjust during change in load and speeds. (Festo 2016a, p. 20.)

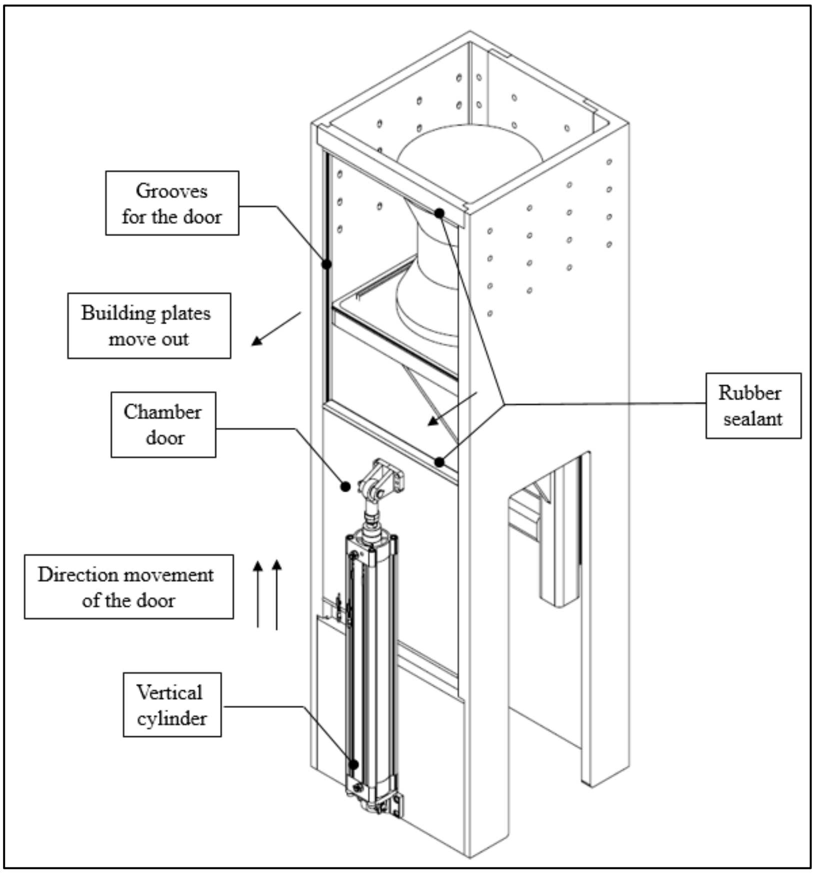

Figure 20. Assembly of the chamber door (mod. Festo 2016a, p. 20).

3.2.5 Retraction unit

The retraction unit is a novel feature built in this machine. As the name implies the retraction unit's main purpose is to retract the finished workpiece and the building plate from the built chamber. The unit is made up of an assembly that contains permanent magnets. The movement of this assembly to and fro is carried out by timing belts and pulleys. They belt and pulley is driven by an Alternating current (AC) motor and gear box. The start position is the outside of the built chamber and the end position is at the conveyor unit.

The permanent magnets are assembled on to the retraction assembly using flat head countersunk screws. The sectional view in figure 21 shows the magnets and screws. The figure also shows the cylindrical rollers and how they are mounter on to the side frames. The entire assembly is mounted to the timing belt using mounting small mounting units. These mounting units are placed 2 on each end and shafts acts as rails. There are 2 parallel running shafts that guides the unit both ways.

The permanent magnets are made of neodymium (neodymium – boron – iron) and have good corrosion resistance. The demagnetization effect on these magnets are minimal. They operate at temperatures as high as 76°C. They are 1 inch in outer diameter and 4 mm thick. They have magnetization power on both the faces. (McMaster-Carr 2015f, p. 3515.)

The cylindrical rollers are made of steel and they are quite stronger than aluminum. There are 2 rollers present in the retraction assembly and are attached to the side columns using cotter pins. They can carry loads up to 1360 kg. The diametrical rollers contains bearings that are sealed and these keep them free from dust and metallic particles giving them a longer life. They are 890 mm inches in diameter and have an axle length of 623 mm. (McMaster-Carr 2015g, p. 1308.)

The rollers steel surface ensures a smooth sliding of the entire workpiece. They are able to withstand heavy loads. The side frames are screwed to the outer walls of the built chamber. The other end of the frame is screwed to the inner surface of the outer cover.

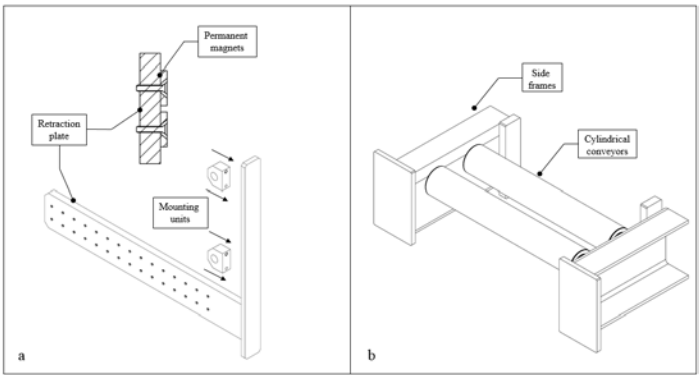

Figure 21. a) Retraction assembly and section view and b) cylindrical rollers (McMaster-Carr 2015g, p. 1308).

The AC motor is controlled by a frequency invertor and has a self-braking system. The speed of the timing belt and pulley is directly influenced by the motor. As the part is lowered into the built chamber, the lifting pins push the building plate upwards. The chamber door slides open downwards to create a space for the workpiece and building plate to move outwards.

The building plate comes in contact with the retraction assembly with the help of magnets. The assembly pulls the workpiece along with the building platform outside on to the conveyor unit. Once new building plates are loaded the retraction assembly takes it into the built chamber and then the electro mechanical cylinder pushes it upwards. Figure 22 shows the overall structure and assembly of the retraction unit.

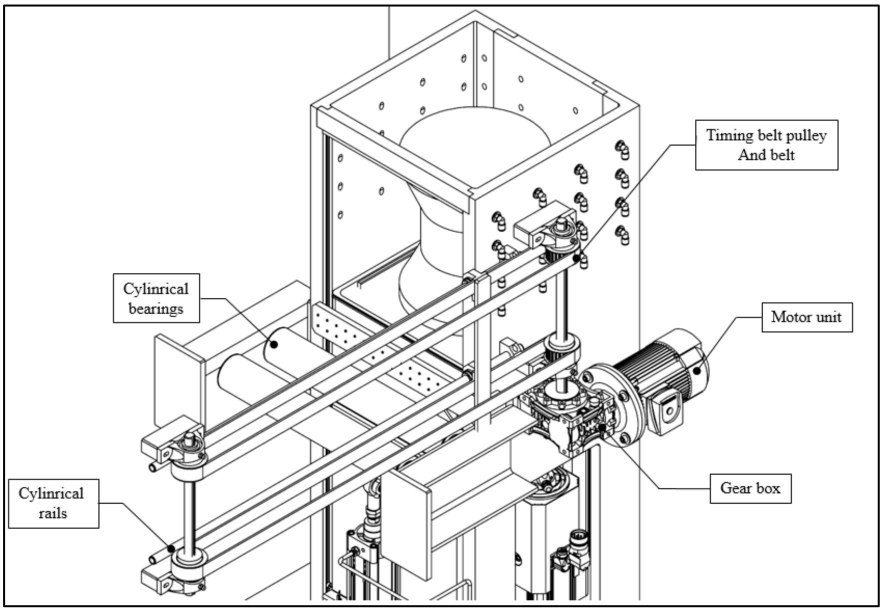

Figure 22. Retraction unit.

3.2.6 Conveyor unit

The conveyor unit is the integral part of the rear modular unit. The conveyor units takes care of the loading of new plates and unloading of finished specimens. The new plates are loaded from the right end from a stacked inventory of plates. The finished workpieces are unloaded to the left end and taken away for post processing applications. The main components of the conveyor units are the chain conveyor, the vertical pneumatic cylinder and the motor and gear unit. Below figure 23 shows the pneumatic cylinder and ball transfer unit

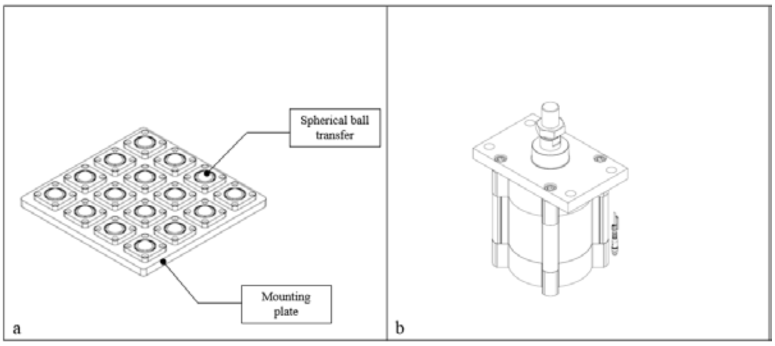

Figure 23. a) Ball transfer unit (McMaster-Carr 2015h, p. 1312), b) Standard pneumatic cylinder (Festo 2016a, p. 2).

The electric motor drives the shaft and the movement of the chain brings the new plate to the center of the conveyor. The conveyor is stopped as the plate reaches the ball transfer unit. The pneumatic cylinder lifts the ball transfer unit and an offset is created from the base surface. The retraction unit plate is now able to push it and take the new plate into the built chamber for the new melting process to begin. The figure 24 shows the independent chain conveyor unit.

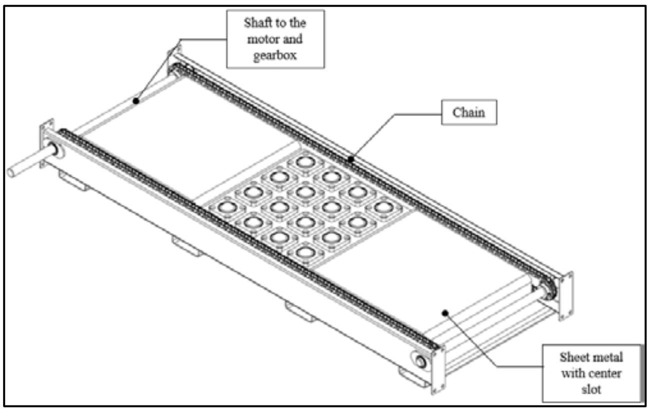

Figure 24. Chain conveyor unit.

The same procedure happens when the workpiece is completed and the retraction unit brings it to the conveyor unit. The ball transfer unit is in the same line as the retraction unit. The pneumatic cylinder then lowers the ball transfer unit into the chain conveyor. The chain conveyor begins to move taking the completed workpiece towards the further right corner. The figure 25 and figure 26 describes the working of the conveyor unit.

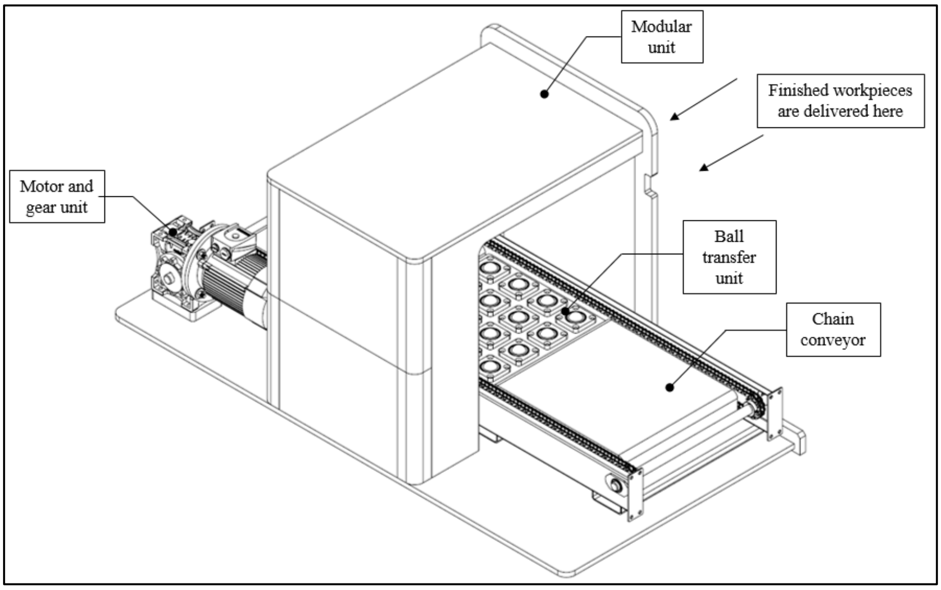

Figure 25. Working and parts of conveyor unit.

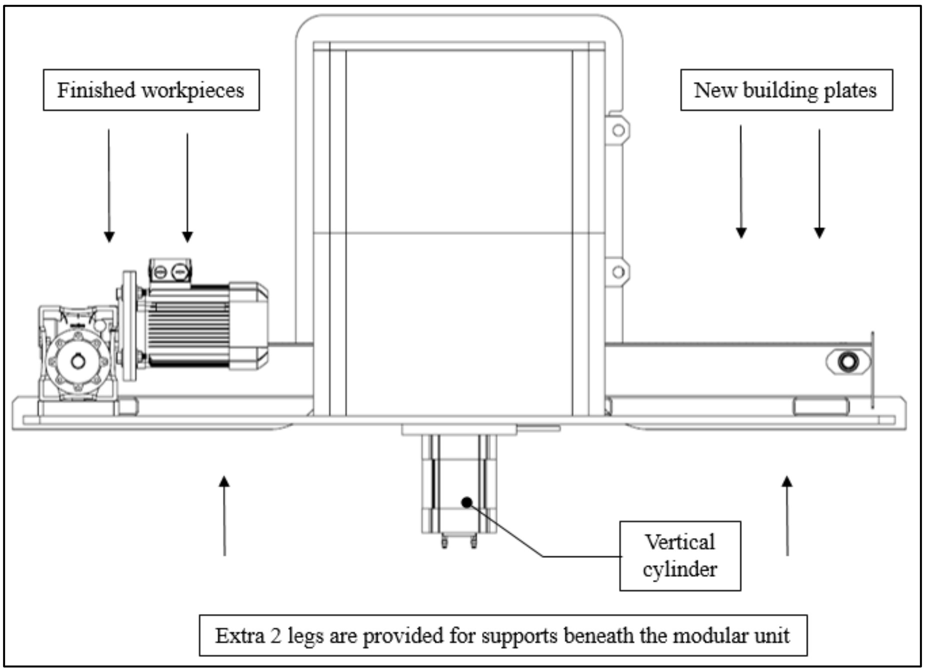

Figure 26. Working and assembly of the conveyor unit.

4 THE POWDER FILTER AND NITROGEN SYSTEM

The powder filter system is an innovative idea installed in this new design of metal AM printing machine. The earlier challenge of manual loading the powder and cleaning of the powder chamber after the workpiece is printed is nullified using this technique. The entire system consists of the following processes namely powder feeding, powder removal and powder filter.

The powder feeding process enables the part production or melting of workpieces to be a continuous process. The powder removal process takes the extra powder out once the part is printed and sends it to the powder filter. The powder filter process continuous and the filtered powder is sent back to the powder chamber for another process. A small remain of unfiltered powder is collected in another chamber.

The nitrogen gas is fed into the powder chamber once the vacuum is created. The nitrogen gas is inert in nature and is directed towards the building platform. The sole reason for the nitrogen gas to be fed into the building chamber is to prevent any contaminants or dust particles to mix with the melting powder particles. It also prevents oxidation and decarburization during the process. It aims at keeping the oxygen content at minimal level. (Spears & Gold 2016, p. 9.)

4.1 Powder unit

The powder unit consists of powder chamber, powder pump, sieving station, filter units and vacuum blower along with powder flow valves. The machine is designed for 316 stainless steel powder. The size of the powder particles is 35 µm. The flow of gases in perpendicular direction to the building direction increases the bonding strength of the powder particles and thereby influences the mechanical properties. (Dadbakshsh, Hao & Sewell 2012, p. 241.)

The particle size influences the density of the melted part, surface roughness and mechanical strength. A mix of fine particle sizes and large particle sizes in comparison can bring about desired mechanical properties. The finer particles undergoes easier melting process and increases the density of the part whereas larger particles reduce the speed of melting and creates lower surface quality. (Spierings, Herres & Levy 2011, p. 201.)

The below figure 27 shows the schematic drawing of the entire powder unit. The powder process explanation is described next and the numbers in bracket relates to figure 27 directly. The built chamber (1) shows is just a reference to the place where the printed part is lowered. Once the printed part is lowered into the chamber high pressure air is blown into the chamber from the walls. Simultaneously vacuum is created using the vacuum blower (8) and the powder is sucked out from the hole in the lower end of the built chamber. This happens due to the fall in pressure between the two chambers.

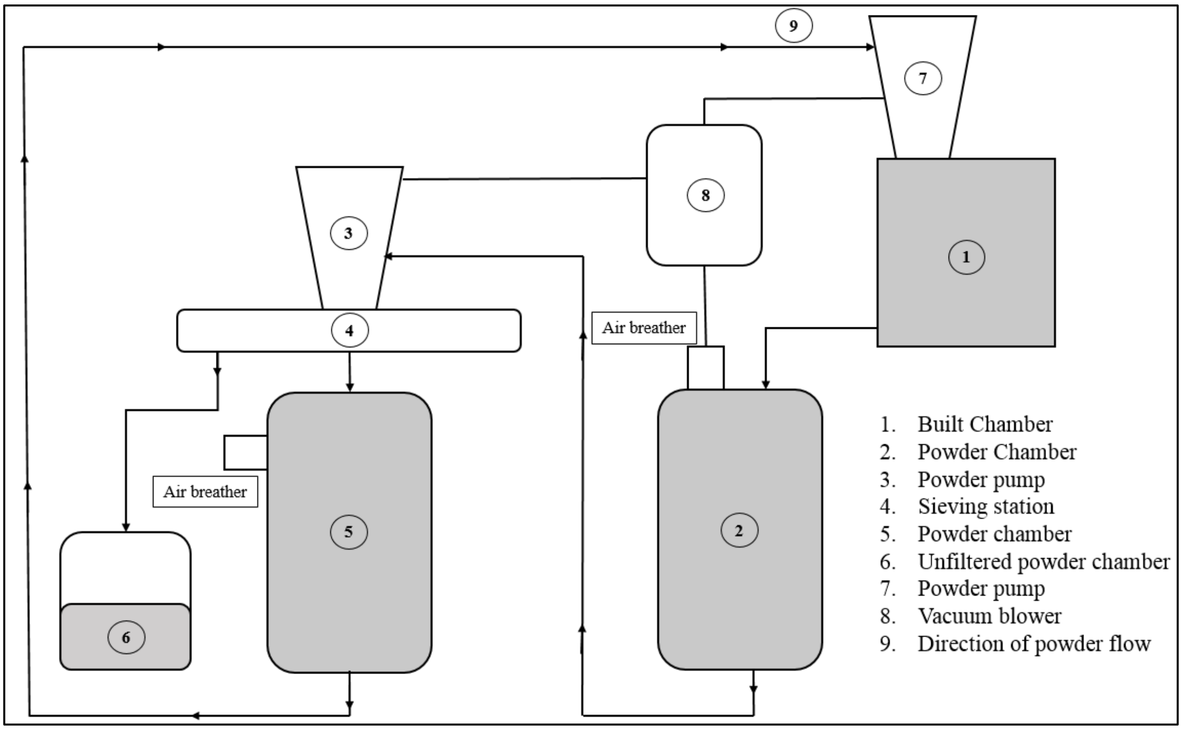

Figure 27. Powder filter schematic drawing.

The vacuum blower now creates a vacuum in the powder pump (3) and the powder is sucked out from the powder chamber (2) into the powder pump. The powder pump (3) collects the powder and transfers it to the sieving station (4). The sieving station filters the powder particles and sends usable powder to powder chamber (5). The unfiltered powder is sent to powder chamber (6). The air breather make sure there that there is clean air passing into the vacuum blower and it collects all the powder particles.

The vacuum blower (8) creates a vacuum in the powder pump (7) and now powder is sucked from the powder chamber (5). The powder is then slowly dropped from the powder pump (7) into the powder reservoir placed inside of the building chamber. This process continuous and ensures there is continuous powder removal and filtration process.

4.1.1 Powder chambers

There are two large powder chambers in the powder unit and one small powder chamber where the unfiltered powder gets collected. The powder chamber are cylindrical in nature and made up of 316 L stainless steel and painted. The walls are painted so that the powder particles do not stick on to the surface of the walls. The volume of the two large chambers are 1.01 x 10^8 mm^3. Figure 28 shows the different components of the powder chamber.

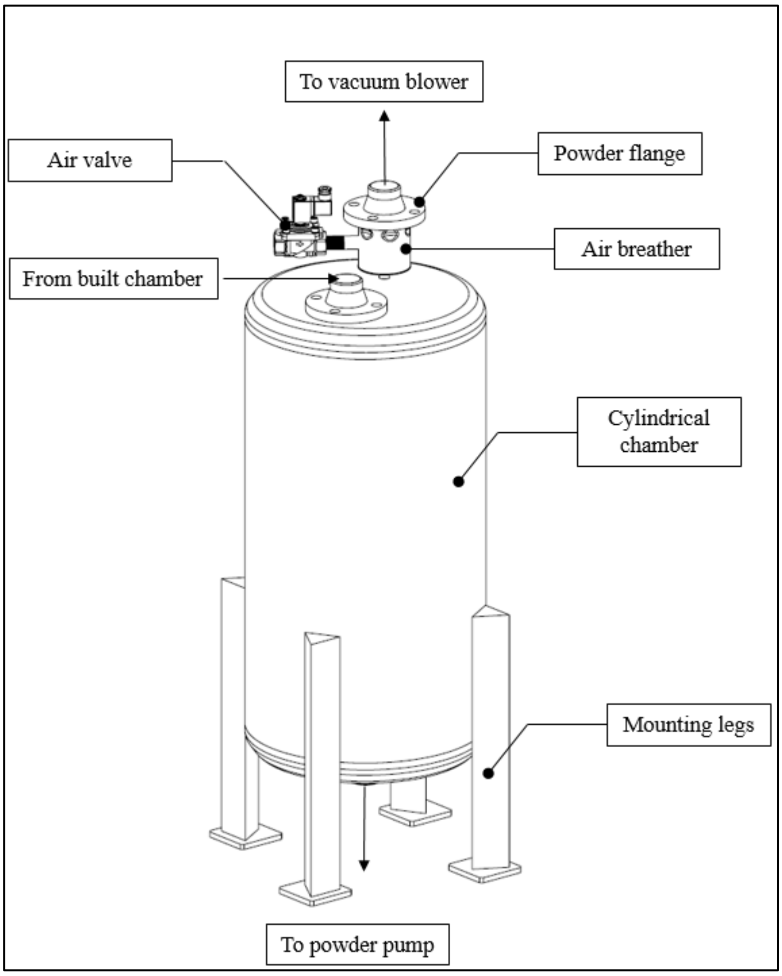

Figure 28. Powder chamber.

The powder chamber consists of the cylindrical chamber those are welded to two cylindrical caps on the top and bottom. The top cap contains inlet port for the built chamber and a port connected to the vacuum blower. The inlet port from the built chamber is welded to a pipe flange. The port connected to the vacuum blower contains an air breather. An air valve is attached on the side of the air breather. Below figure 29 shows the air breather, pipe flange and air valve independently.

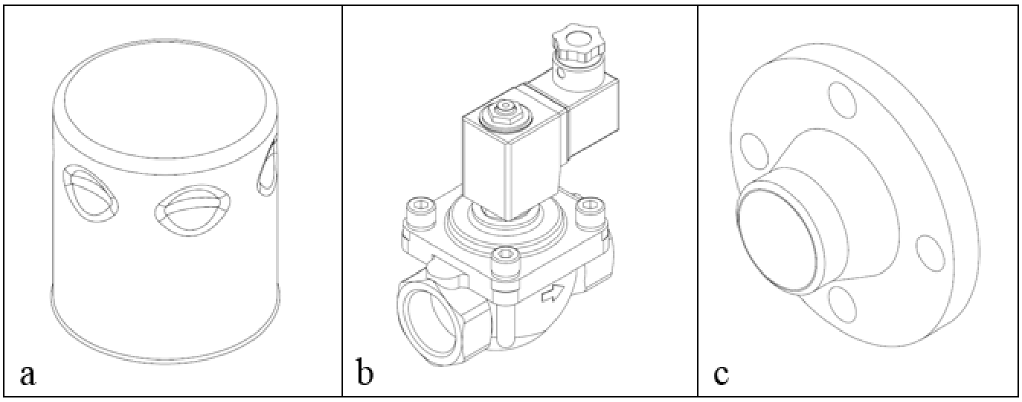

Figure 29. a) Air breather (mod. Airfil Oy, p. 5), b) Air valve (Festo 2016m, p. 6) & c) Pipe flange (McMaster-Carr 2015i, p. 24).

The air breather is mounted on a welded 3/4 - 14 BSPP male thread rod. This is placed inside an enclosure of another tube. The working temperature of this ranges from -10°C to 110°C. The maximum flow range is 150 l/m. (Airfil Oy, p. 5.) The air breather functions when the air valve is closed. The vacuum blower sucks the air through this filter.

The air valve is an electrical actuated valve. The flow rate of air is 11 m^3/h. It is made up of brass material and have operating conditions at ambient temperature ranging from -10°C to 35°C. It weighs about 1.5 kg. (Festo 2016m, p. 9.) The valve is used to let the flow of air in and out of the pipe surrounding the air breather.

The pipe flange is used in many instances of the machine. It is made of stainless steel and can assemble 2 inch diameter pipes. This flange is mounted using 5/8 -16 socket head cap screws. They have high corrosion resistance. The followability of the powder particles is also quite high. (McMaster-Carr 2015i, p. 24.)

4.1.2 Powder pump

The powder pump is used to receive powder from the lower powder chambers and discharge it to the powder feeder placed in the building chamber. There are two powder pumps on this system. One is attached directly to the powder feeder in the main chamber and the other is placed over the sieving station. This guides the powder flow from a lower level to a higher level.

The powder pumps used here are Coperion K tron powder pump. The powder discharge is a done by a butterfly valve controlled by gravity only. There is always powder present in the powder pump which is monitored using sensors. Below figure 30 shows the powder pump and important ports. (Piispa 2017a.)

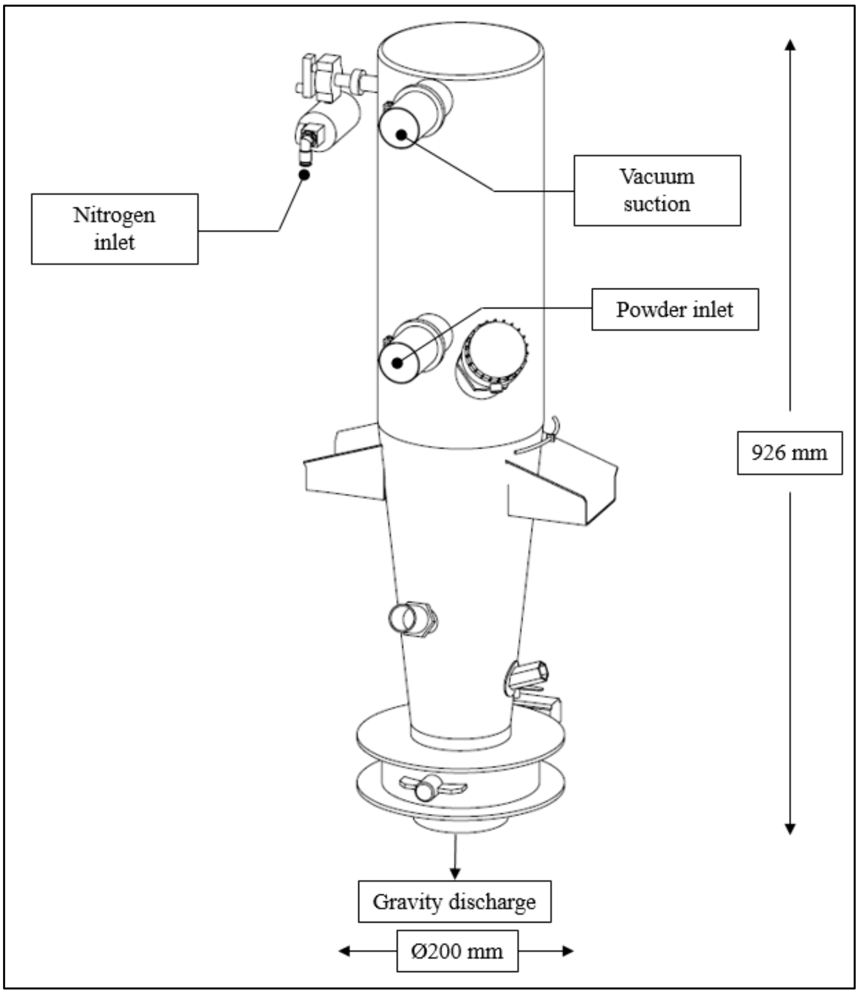

Figure 30. Powder pump (mod. Piispa 2017a).

The pump is made of stainless steel and is electroplated. The welding is carried out smoothly ensuring the smooth flow of the powder while discharge and inlet. The fittings are easy and quick to remove hence service and cleaning of the powder pumps is an easy process. The flow of powder process through the pump is controlled by a Loaded, Single receiver (LSR) controller. (Piispa 2017a.)

The operating temperature ranges from -10°C to 50°C. The conveying rate of powder is 400 kg/h (800 lb/h). The holding capacity of the pump is 7.8 dm^3. The clamps around the pump is made of stainless steel and is corrosion resistant. The butterfly valve has a rubber sleeve to make the pump powder tight and ensure clean flow at gravitational discharge. (Piispa 2017a.)

4.1.3 LSR controller

The LSR controller is installed on both the powder pumps. They integrate the vacuum blower and the powder pump together. The controller is precise, safe and robust, handling multiple applications and configurations. There are pre-installed wires on the powder pump which are connected to the LSR controller. The LSR controller is connected to an input voltage of 24 Direct Current (DC). Below figure 31 shows the LSR controller. (Piispa 2017a.)

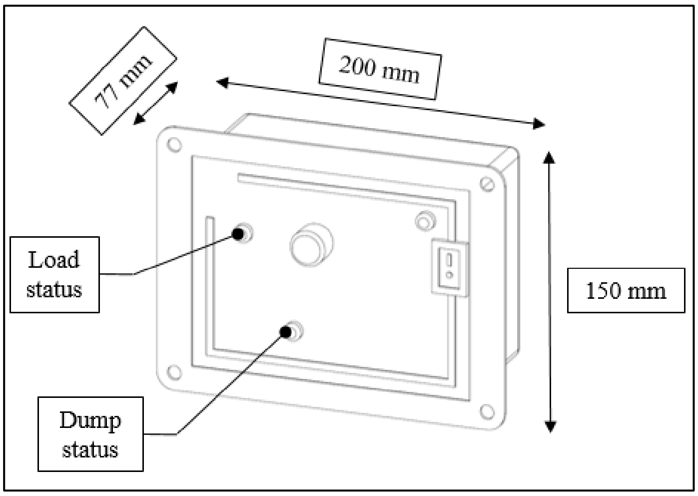

Figure 31. Standard LSR controller (Piispa 2017a).

The LSR controller is made of durable polycarbonate and contains an ON/OFF switch in the front panel. It has a Light Emitting Diode (LED) screen that signals power/alarm, dump status and load status. An internal rotary switch is available in the controller for different modes of operation. The mode of operation used here is single central receiver, gravity discharge and fill to level. (Piispa 2017a.)

The LSR controller transfers a signal when the gravity gate is close and powder starts filling into the powder pump. A sensor is available to check the height of powder being filled in the pump. If there is a gap in filling the material within the stipulated time an alarm signal is generated and the filling continues. Once the powder fills the prescribed level the gravity gate closes. (Piispa 2017a.)

4.1.4 Sieving station

The sieving station present in the powder system is used to separate the unfinished or melted particles that are not a part of the completed workpiece from the fine powder particles. The sieving station contains a sieve that filters particles greater than 32µm. The maintenance and spare parts of the assembly is easy. Below figure 32 shows the sieving station from Ab Brynolf Grönamrk. (Piispa 2017b.)

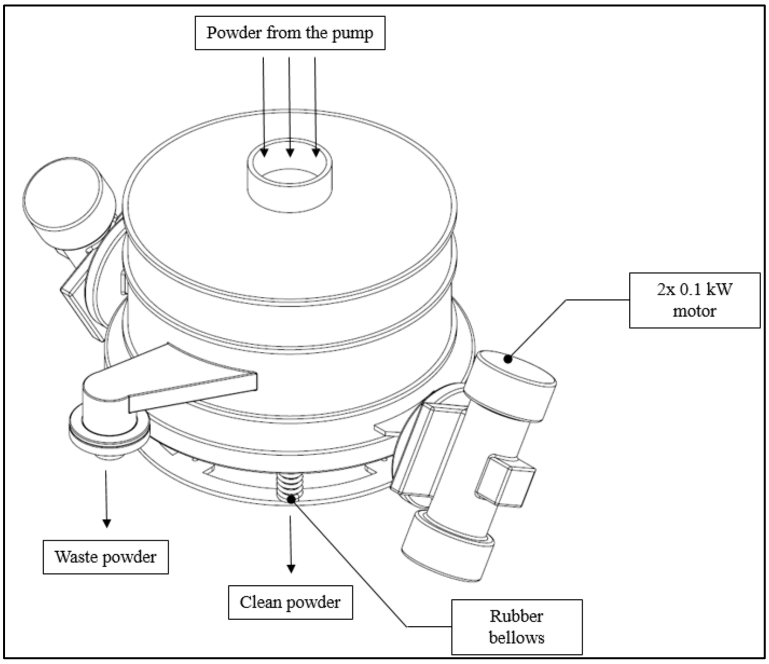

Figure 32. Sieving station (mod. Piispa 2017b).

The main frame and structure of the sieving station is made from 304 stainless steel and have a diameter of 1000 mm. The outer cover has epoxy coatings. The outer cover is also made of 304 stainless steel with rubber material. It contains 4 rubber flexible bellows made of

Neoprene having a length of 8 inches. The mesh is made of 316L stainless steel. The motors present in the sieving assembly has a power of 0.1 kW and runs at 1450 rpm with 50 Hz. It requires an input voltage of 400 0.1 kW, 1450 rpm, 50 Hz, 400V. (Piispa 2017b.)

The sieving station is placed on the left module of the machine just below a powder vacuum pump. The integration of the sieving station into the printing machine makes it easier to clean and handle the powder efficiently. The gravity gate present in the vacuum pump opens and the powder is streamlined into the sieving mesh through the pipe flange. The two motors present on either sides of the sieving assembly generates the vibration required for the mesh to filter.

The powder particles mix contains fine particles that have not undergone melting under the laser along with powder particles that are semi melted. These particles makes the mixture unsuitable to be used again. The mesh filters these large particles and sends it to the unfiltered powder chamber. The filtered powder is pumped back into the powder pump present in the building chamber.

4.1.5 Vacuum blower

The vacuum blower is present to increase the efficiency of the flow of powder particles created by the powder pump. It supplements the flow by creating a pre vacuum or blowing a vacuum. The powder particles as it travels become slow at the different exit ports and the vacuum blower makes sure that the flow of particles is smooth with a constant velocity. The flow of powder can remain constant without any movement at specific intervals. The vacuum blower ensures that there is the unchanged velocity as earlier before the flow of powder stopped. (Thiele 2012, p. 80.)

The vacuum blower in this machine is from K-tron Cooperion. They are efficient in blowing the small granular powder materials. As the travel distance is short this blower makes it efficient in this machine to operate on a continuous basis. The curved blades in the motor guarantees a clean suction of air flow with required efficiency. The below figure 33 is the design of the vacuum blower in this system. (Piispa 2017a.)

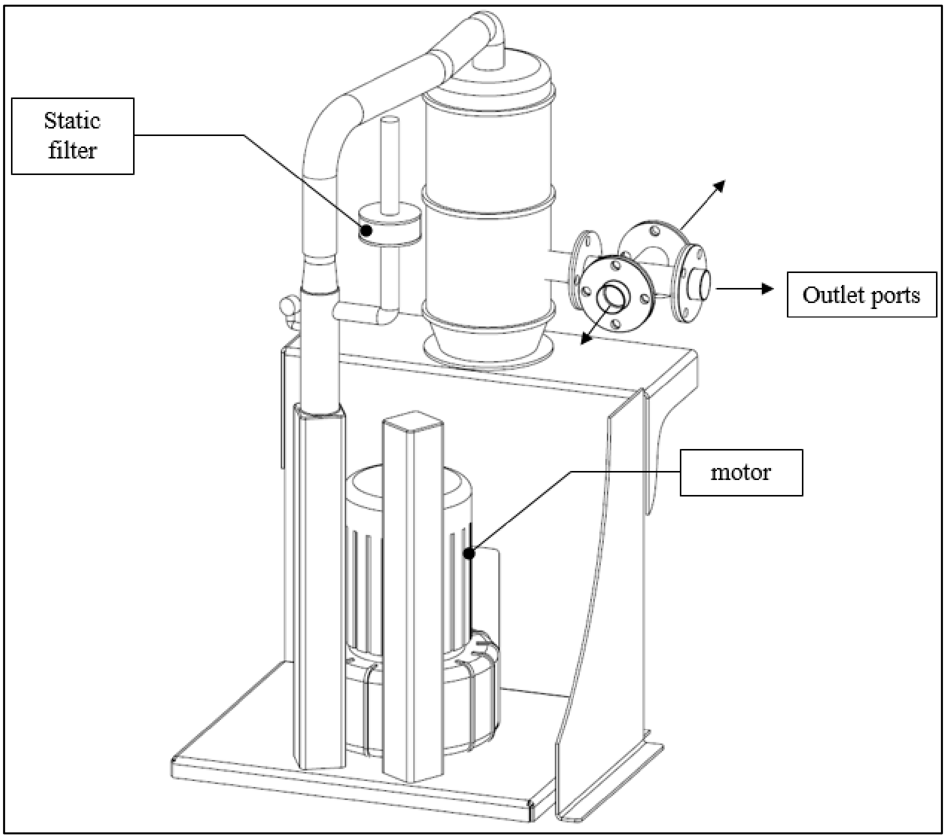

Figure 33. Vacuum blower (mod. Piispa 2017a).

The blower consists of a heavy plate that it is mounted upon to have easy access to cleaning and servicing the unit. Isolation pads are placed between the mounting plate and the blower to reduce the noise or dampen vibrations that are caused by the motor. The normal sound ranges from 74 to 79 dB but they can be brought down by installing sound reducers. (Piispa 2017a.)

The blower operates at a voltage 400 volts and has a maximum flow rate of 338 m^3/h at 60 Hz. The entire unit weighs to 89 kg and the motor has 4.8 horse power. A discharge silencer is also present in the vacuum blower and the motor is void of belt or gears i.e. it is a direct drive motor. There is no requirement for oil as lubrication. The vacuum blower has single outlet port and is connected to a 3 way flange. Two of the flanges are connected directly to each of the vacuum pump and one of them is connected to the initial powder chamber which sucks the powder out from the built chamber. (Piispa 2017a.)

4.2 Nitrogen unit

The nitrogen unit present in the machine drives two purposes. The first purpose is to have the nitrogen circulation above the building platform and the second purpose is to cool the scanner head. The nitrogen is circulated in the machine, filtered and then sent back to the chamber again. Below figure 34 shows the schematic circuit of the flow of nitrogen gas in the machine.

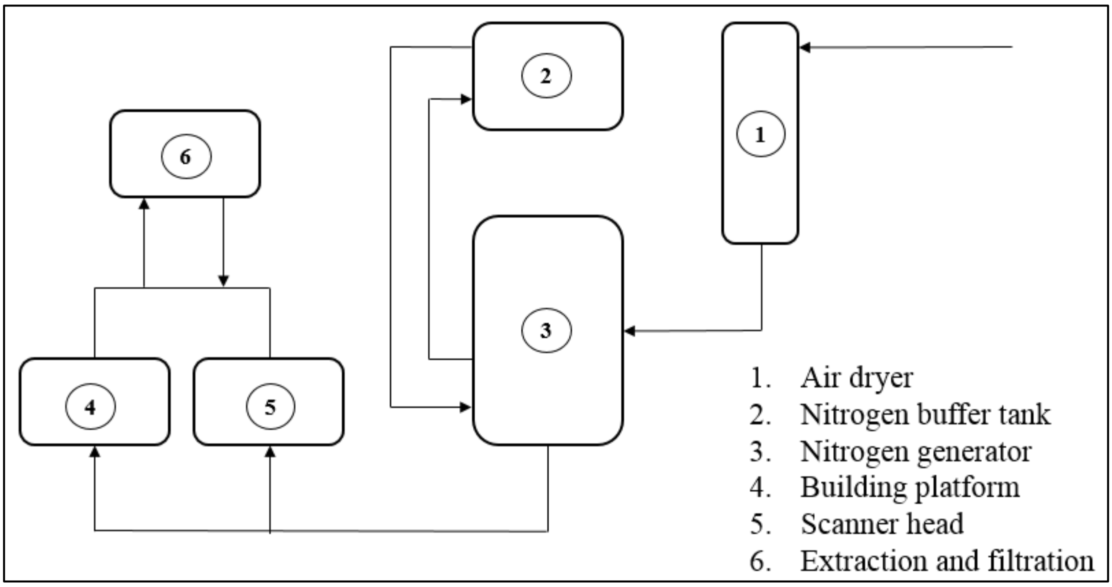

Figure 34. Schematic sketch of the Nitrogen system.

The nitrogen air flows through pneumatic tubes and contains solenoid directional valve, split connecters, flow control valves, flow sensor valves and delivery valves. The nitrogen gas is connected to the vacuum powder pump providing cooling to the flow of powder inside the chamber. The valves and connectors of the pneumatic system have been chosen from Festo Corporation.

The direction control valve used here is a 3/2 electrically actuated direction control valve. It directs the flow of nitrogen between the nitrogen generator (2) to the building platform (4) and scanner head (5). The both entries exist at the same building chamber. The housing of the valve is made of aluminum alloy and is mounted on the lower plate of the laser and control unit. The operating temperature of the valve in ambient temperature ranges from -5°C to 50°C. The operating pressure has a range from 0.9 to 10 bar. The reset of position is carried out by mechanical spring. There are 2 Direction control valves (DCV) combined into a single unit and has a silencer attached to the unit. Below figure 29 shows the structure of the modular unit. (Festo 2016h, p. 1)

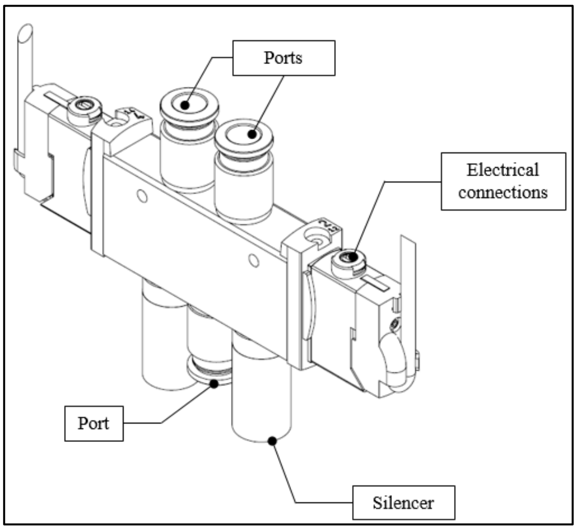

Figure 35. 3/2 solenoid operated direction control valve (mod. Festo 2016h, p. 1).

The one way flow control valve ensures the flow of nitrogen gas in just one direction. The reverse flow is blocked by a ball in the opposite direction. The flow control valve in this machine has pneumatic quick star port fittings at the inlet and outlet. The operating pressure ranges from 0.2 to 10 bar and has an ambient temperature conditions ranging from -10°C to 50°C. It weighs to 0.023 kg and has an outer casing made of alloy steel and has a flow rate of 0.004 m^3/s. They are connected to the tubes and mounted using strap clips. Below figure 36 shows the design of the one way flow control valves. (Festo 2016g, p. 1.)

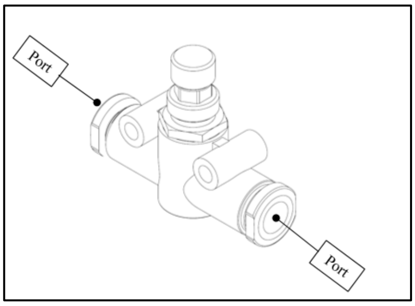

Figure 36. One way flow control valve (mod. Festo 2016g, p. 1).

The flow sensor valves monitors the flow of the nitrogen gas within the pneumatic system. It is an open valve and shuts of the entire system if there is an excess flow rate. The flow rate can be monitored on the screen of the flosw sensor valve. It is mounted onto the plate using screws. The lowest flow rate is 3.3 x 10^{-5} m^3/s and the highest flow rate is 0.003 m^3/s. It weighs to 0.6 kg and has a blue illuminated Liquid Crystal Display (LCD) display. The operating ambient temperature rages from 0°C to 50°C. Below figure 37 shows the model of the flow sensor valve. (Festo 2016i, p. 1.)

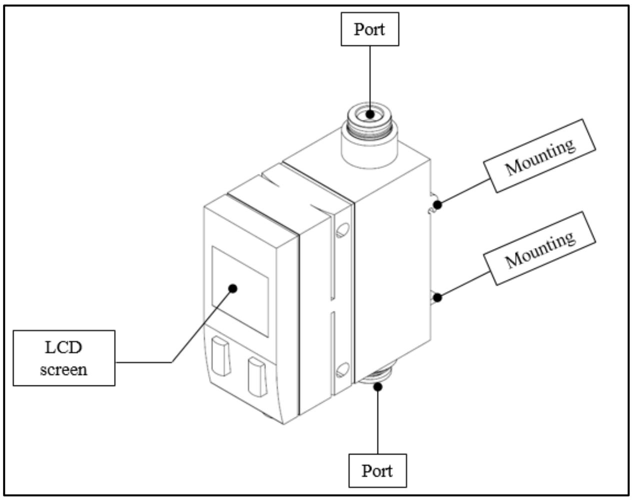

Figure 37. Unidirectional flow sensor valve (mod. Festo 2016i, p. 1).

The basic function of the check valve is to have a unidirectional flow and prevent the flow of nitrogen gas in the reverse direction. The check valve in this circuit is a non-return valve having a flow rate of 0.011 m^3/s. The operating temperature lies between 0°C to 60°C at an operating pressure between -1 to 10 bar. It weights to 0.021 kg and has a housing made of aluminum. Below figure 38 shows the model of non-return valve. (Festo 2016e, p. 1.)

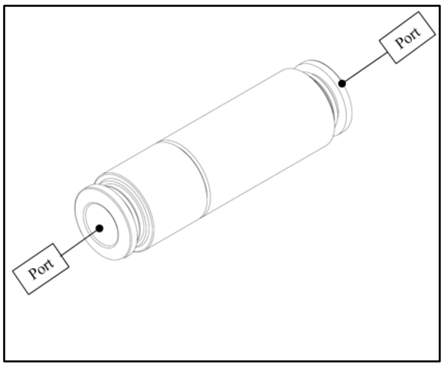

Figure 38. Unidirectional non-return (mod. Festo 2016e, p. 1).

The nitrogen buffer tank is connected to the 3/2 direction control valve which is then directed towards the non-return flow control valve. The sound of leakage of nitrogen is reduced by the silencer. The non-return flow control valve is then connected to the flow sensor valves. The flow sensor valve is then connected to the non-return check valves and then finally sent to the building platform and scan head respectively. Six ports are connected at the entrance of the building platform and two ports are directed to the scan head. Below figure 39 is the pneumatic circuit of the entire system.

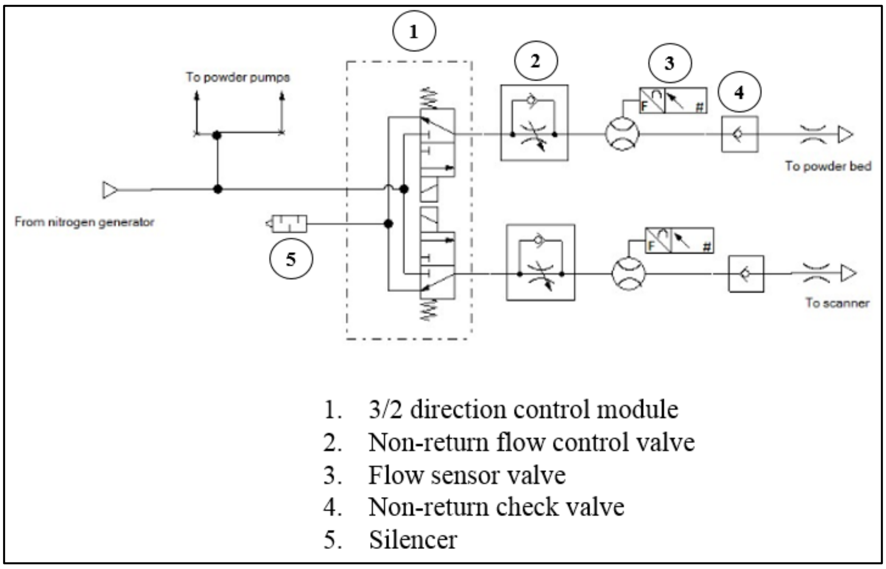

Figure 39. Nitrogen system schematic circuit.

4.2.1 Nitrogen generator

Nitrogen is required in the building platform to reduce oxidation during the melting process. It acts as a cover for shielding the melting process and enhancing melting properties. The flow of nitrogen occurs perpendicular to the direction of building. Nitrogen ports exists on either side of the building platform. The nitrogen generator produces nitrogen from standard compresses air.

The nitrogen generator present in this machine is MIDIGA S2 from Parker weighing 98 kg. It works at an ambient temperature range from 5°C – 50 °C. The outlet pressure of nitrogen gas is 11 bar. It requires a voltage of 230 volts and has inlet and outlet ports with ½ ″ NPT. Below figure 40 depicts the design of nitrogen generator MIDIGA S2. (Parker 2012, p. 14.)

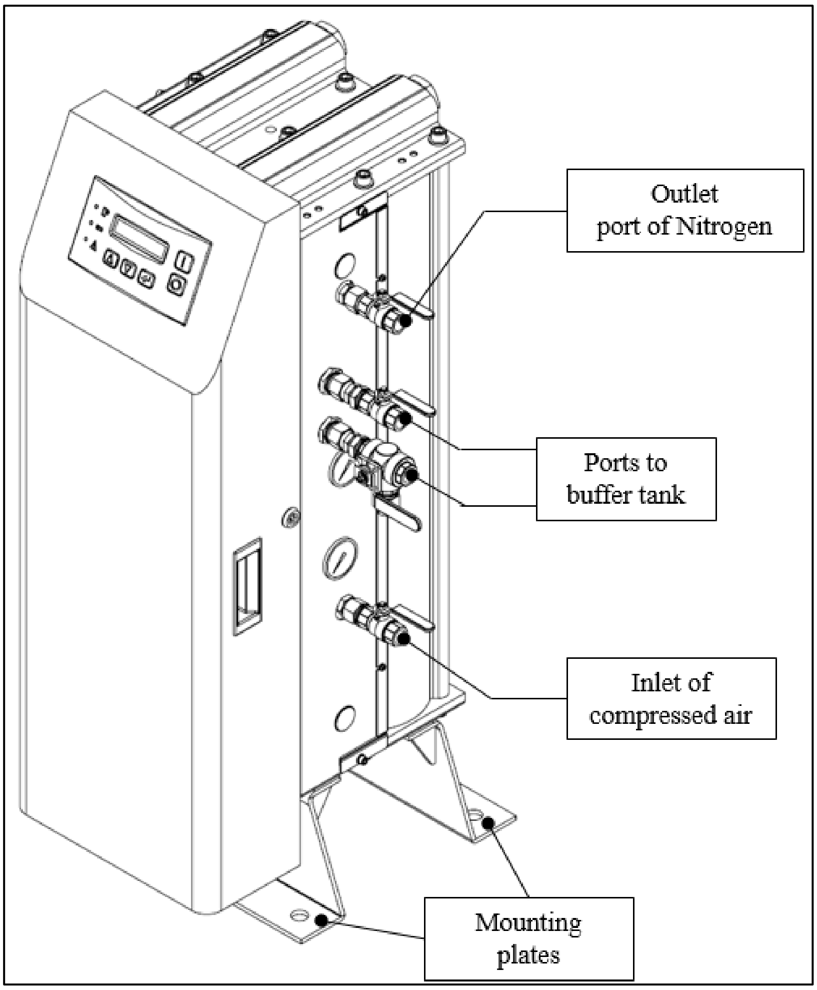

Figure 40. MIDIGA S2 Nitrogen generator (Parker 2012, p. 14).

The MIDIGA S2 requires an inlet of compressed air and converts it into nitrogen with the help of carbon filters. The carbon filters removes the oxygen content and produces nitrogen at low pressure which is safe to use. It is an energy saving generator and has less carbon foot print which is essential for the surrounding. The interface is easy to use and the modular design is installed easily in the machine in the right chamber. (Parker 2012, p. 14.)

The nitrogen gas is used in the building platform and also sent to the vacuum pumps. Standard piping is used to connect to the buffer tank and the air dryer. The nitrogen generator is capable of supplying a continuous flow of nitrogen 24 x 7. The inbuilt nitrogen generator has an advantage of not having to refill gases, tank rentals and the prices of gases does not inflict the machine. The generator has a lower maintenance and service time reducing the disruption of the process. (Parker 2012, p. 2.)

4.2.2 Buffer tank

The nitrogen buffer tank has a capacity to hold up to 50 l of nitrogen gas. The gas is stored here in shortage of nitrogen required in building platform and vacuum chamber. The shortage can occur during preparation of nitrogen gas within the nitrogen generator. To ensure a continuous printing process with a constant supply of nitrogen gas, the buffer tank stores and supplies to the required areas during printing of the workpiece. Below figure 41 shows the overall dimensions of the buffer tank.

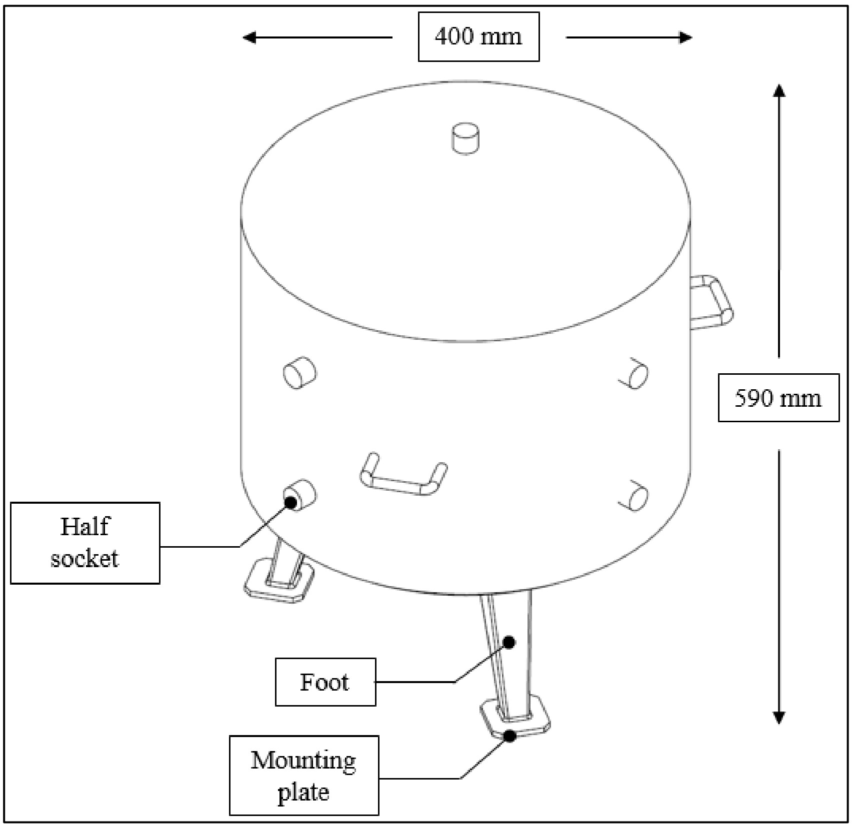

Figure 41. Nitrogen buffer tank (Piispa 2017c).

The half socket ports in the buffer tank are connected to the nitrogen generator. The nitrogen buffer tank also serves as a unit to maintain the pressure of the nitrogen gas as same to the atmospheric pressure and also increase the purity if the gas. The buffer between the pipe and receiver end does not suffice for the melting process and buffer tank is installed to eliminate this issue. The buffer tank supplies nitrogen when the nitrogen generator undergoes service or maintenance. This enables the machine to have a continuous production without any blockage caused by the absence of nitrogen generator. (Bodemann & O’Connor 2014, p. 4.)

The buffer tank is designed to have 3 foots with mounting plates and they are installed on the right side of the machine behind the buffer tank. The size is approximately 590 mm x 400 mm (Height x Outer Diameter) which makes it easy to assemble within the machine unit. It operates at temperature from -40°C to 50°C with a pressure bar ranging from 0 to 10 bar. The buffer tank has components made of 304 L stainless steel and is welded together. (Piispa 2017c.)

4.2.3 Air dryer

The compressed incoming air from standard supply units carry a minimal amount of moisture and residual particles. This affects the purity of nitrogen gas being generated using the nitrogen generator. The presence of moisture in the air can cause corrosion and sometimes blockage in the valves as the compressed air passes through. The presence of oil and residue particles increases the chance of corrosion in the system. The compressed air dryer unit resolves this issue. Below figure 42 shows the compressed air dryer unit present in the metal AM machine. (Parker 2015, p. 2.)

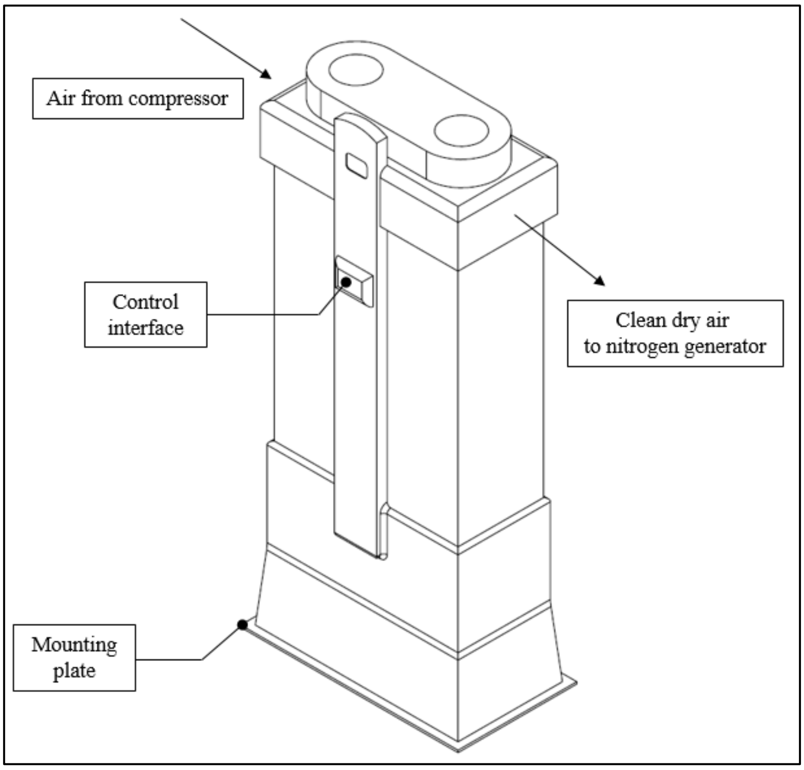

Figure 42. Compressed air dryer (Parker 2015, p. 10).

An after cooler is present to remove the moisture from the incoming compressed air in this unit. The temperature of the air is also reduced and the filtration package removes the residual particulate present in the compressed air collected from the atmosphere. A part of the air that is already dried using the desiccant material is used to regenerate the desiccant material as water vapor is collected on the surface. This is a regenerative process and ensures clean, dry and efficient air. (Parker 2015, p. 4.)

The compressed air dryer used in this machine is the PneuDri MiDAS1 which has a flow rate of 0.001 m^3/s. The high quality of air prevents microbial growth and also resists corrosion. The alochroming and epoxy painting of the air dryer also makes it corrosive resistant thereby reducing service and maintenance. It requires a 230 V supply and has ports in NPT. An outlet dust filter is also assembled with this unit. (Parker 2015, p. 11.)

4.2.4 Extraction and Filtration

The laser in the presence of nitrogen gases prints the workpiece layer by layer. During the printing process fumes are created and it mixes with the nitrogen air. The nitrogen air in the air now contains minute powder particles. The nitrogen air is taken out from the rear portion and sent to the extraction and filtration unit present in the lower section of the middle chamber. Below figure 43 shows the extraction and filtration unit present in this machine.

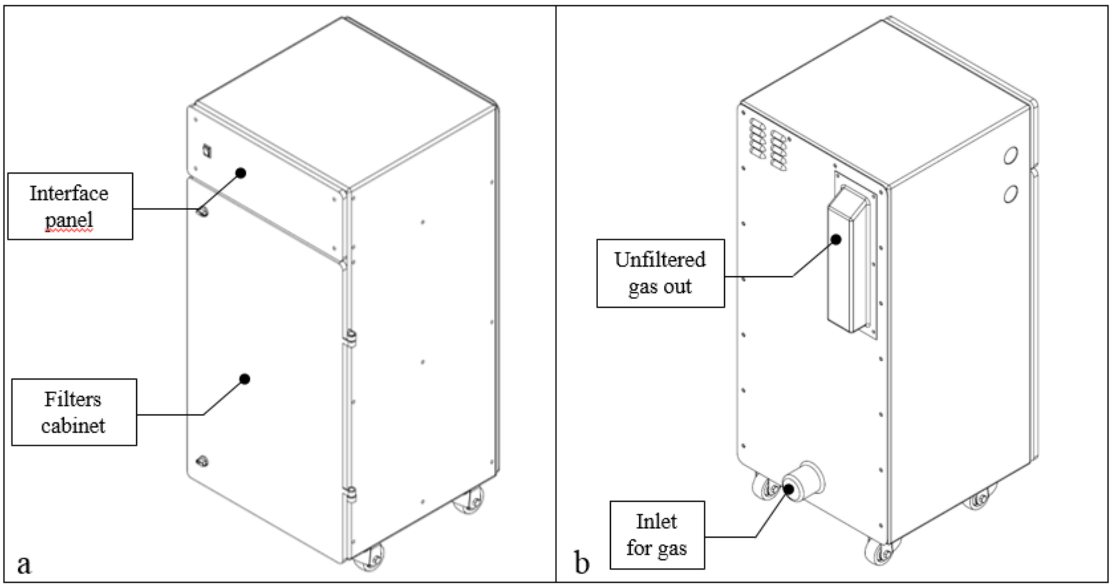

Figure 43. a) Front – iso view & b) Rear – iso view (BOFA 2013, p. 1).

The extraction and filtration unit is model AD Nano+ from BOFA. It is a cost effective solution with an optimized performance and filter longevity. The auto voltage sensing turbine present ensures the machine is operated anywhere around the world. It produces very less nice and the carbon footprint is low which is good for the machine and environment. It contains three filters namely pre filter, High-efficiency particulate arrestance filter (HEPA) and chemical filter. The filters are replaceable components and the entire housing is made of stainless steel. (BOFA 2013, p. 2.)

The unit is operated using a 230 V supply of current and weighs 45 kg. The flow of nitrogen air into the unit is 0.08 m^3/s. The contaminated air flows into through the 50 mm duct and passes to the filters. The large sized metallic particles fall to the lower part of the chamber due to gravity. The pre filter the removes the medium sized particles. The gas is then passed through the HEPA filter and minute particles are held in a 6 m^2 area of filet media. Finally the nitrogen gas passes through the chemical filter and this air is then sent again to the building chamber for usage. (BOFA 2013, p. 2.)

4.3 Pneumatic systems

The machine is completely electrical and pneumatically operated. Pneumatic system in the machine operates the closing of the built chamber after the printing parts is lowered, the opening of the built chamber door to move the finished workpiece out, the movement of the roller inside the powder feeder, the cylinder to lift the ball conveyor unit and the supply of air to the built chamber to remove the powder. The below table 2 shows different pneumatic components and their function.

Table 2. Pneumatic components and function.

S.No	Component	Quantity	Function
1	Hand Slide valve	1	ON/OFF the flow between the compressed air unit and the pneumatic system
2	Filter and Regulator unit (FR)	1	Filters the incoming air and regulates the pressure
3	Check valve	13	Allows the flow of air only in one direction
4	Y splitter	25	Splits the pneumatic ports more than once

Table 2 continues. Pneumatic components and function.

S.No	Component	Quantity	Function
5	Sleeve connector	24	Connector between Y splitter to avoid short pneumatic pipes
6	One way flow control valve	4	Flow of control in one direction but can also regulate the flow
7	Push in fitting	A/R	Before and after valves to ensure tight fittings
8	Manifold assemblies	2	• 5/2 DCV (4 quantity) • 3/2 DVC (12 quantity)
9	Silencers	4	Attached to the manifold assemblies

The below figure 44 shows the main assembly of the pneumatic systems. The hand operated valve and FR unit are common for the two main pneumatic lines. The initial Y splitter splits the pneumatic lines to the direction control valves manifold assemblies. The 5/2 direction control valve is connected to all the pneumatic cylinders in the machine and the 3/2 direction control valve is used for the powder blowing into the built chamber.

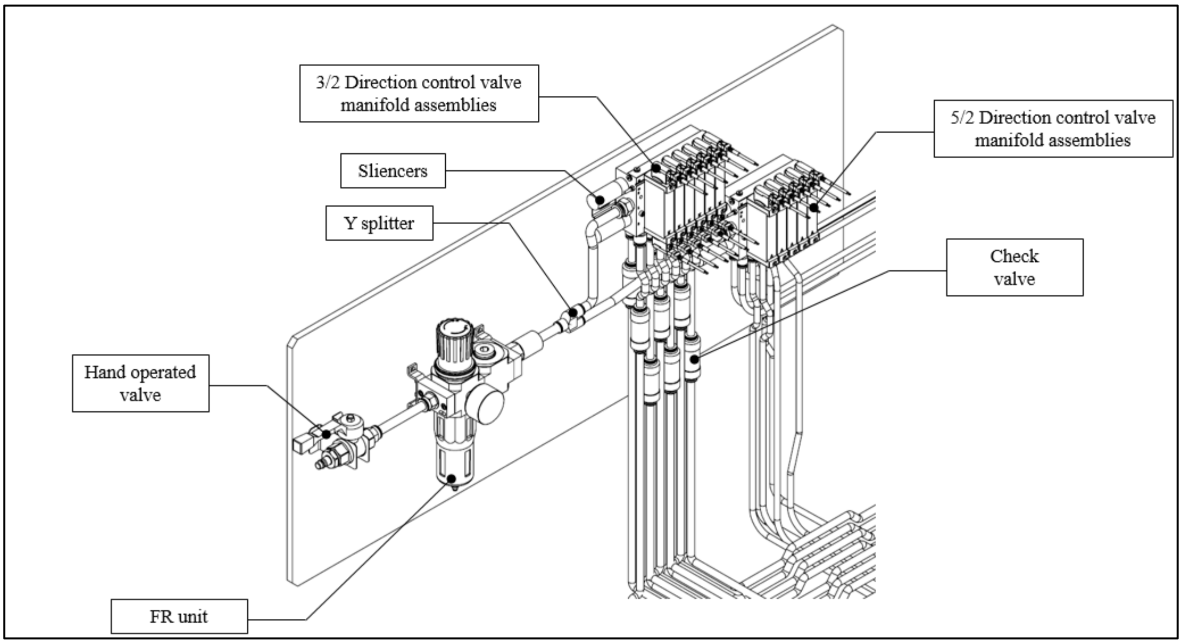

Figure 44. Main components of the pneumatic system.

4.3.1 Hand operated valve

The hand operated ball valve is used to ON/OFF the flow of air from the standard compressed supply of air. This is kept ON most of the time the machine is in function and will be used only while service to not let the existing air in pipes escape and created noises. It has G ½ entry and exit ports. The operating temperature lies between -20°C to 180°C. The nominal flow rate of the gas is 11.500 l/min. The hand operated handle can be turned to 90° to control the flow of gas. It is easy to operate and handle. Below figure 45 shows the hand operated valve. (Festo 2017a, p. 1.)

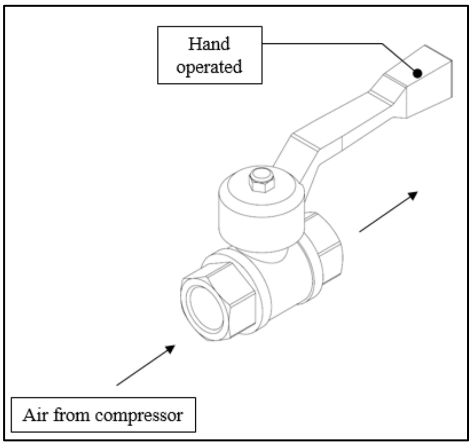

Figure 45. Hand operated ball valve (Festo 2017a, p.1).

4.3.2 FR unit

Most of the air collected in the compressor from atmosphere contains moisture and dust particles. These are not good for the pneumatic system and cylinders while functioning. The FRL unit contains filters and regulators for the incoming air to make it suitable for the pneumatic system. By regulating the pressure the air supply can be cut off if the pressure of air exceeds operating conditions.

The grade of filtration in this unit is 40µm and operates between 1 and 16 bar. It is made up of zinc material and has an operating temperature between -10°C and 60°C. It has G 1/2 entry and exit ports. The filter contains a condensate drain which can be removed separately. There are mounting brackets which is used to attach it to the plate on the wall of the unit using screws. Below figure 46 depicts the FR unit. (Festo 2017c, p. 1.)

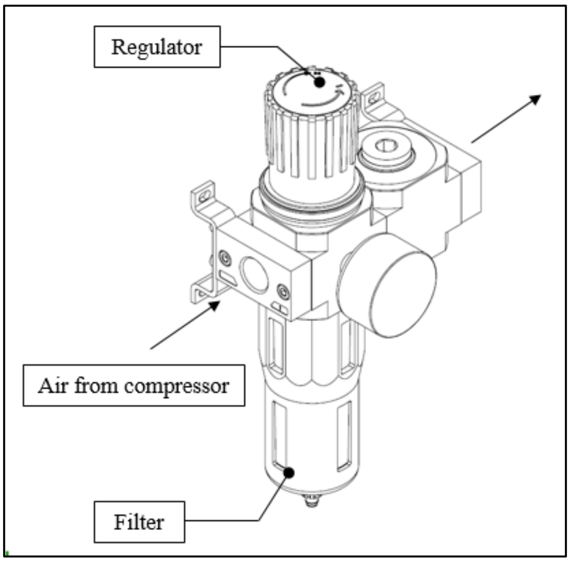

Figure 46. Filter and regulator service combination (Festo 2017c, p. 1).

4.3.3 Manifold assemblies

There are 2 manifold assemblies present in the machine; the 5/2 direction control valves and 3/2 direction control valves. The direction control valves are used to control the flow of the gas in and out of the cylinders enabling them to extend and retract. Both the assemblies are solenoid operated and returns back to closed conditions using spring. Below figure 47 shows both the configuration present in the machine.

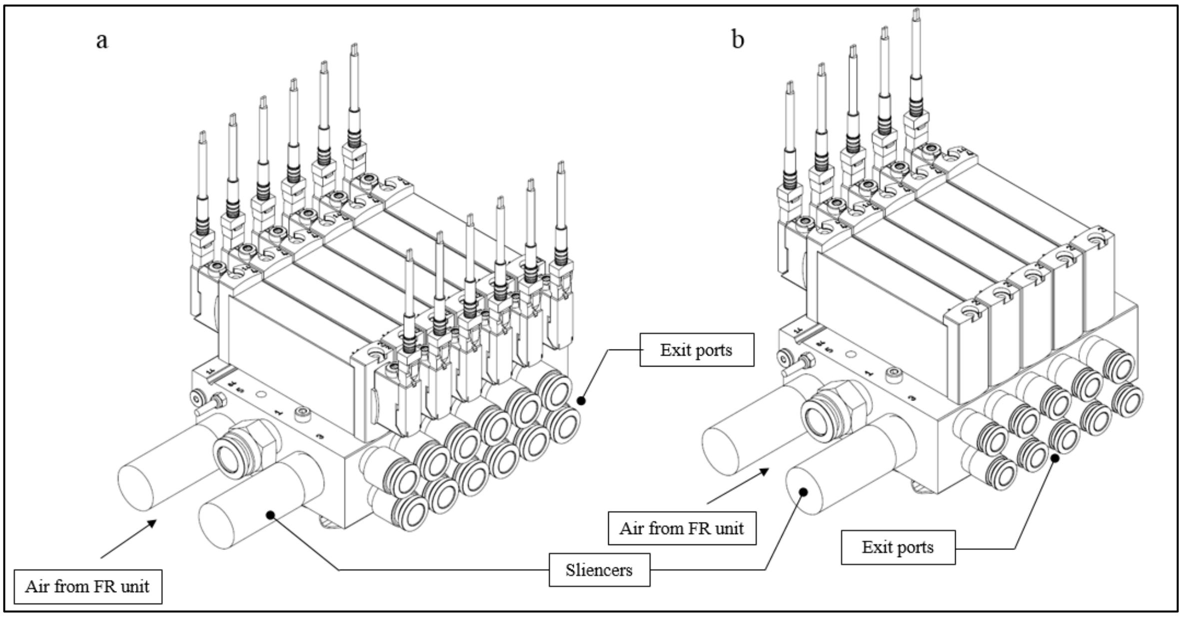

Figure 47. a) 5/2 DCV manifold assembly & b) 3/2 DCV manifold assembly (Festo 2016j, p. 1).

Both the assemblies have operating pressure range from 0.9 to 10 bar. The ambient temperature working conditions are from -5°C to 60°C. They are both electrically actuated and have individual electrical connections. The 5/2 DCV has a reverse flow of gas which allows the cylinder to move forward and retract. The 3/2 DCV does not have a reverse flow. They are used to articulate the flow of gas directly into the built chamber at high pressure to remove the powder from the chamber. (Festo 2016j, p. 1.)

4.3.4 Check valve and Flow control valve

The check valve function is to stop the flow of gas in the reverse manner. It allows the flow of gas only in one direction. The standard nominal flow rate of the check valve present in this pneumatic line is 2.4 x 10^{-5} m^3/s and has an ambient working temperature of 0 to 60°C. The entire housing is made of aluminum and weighs to 0.06 kg. Below figure 48 shows the check valve and flow control valve. (Festo 2016f, p. 1.)

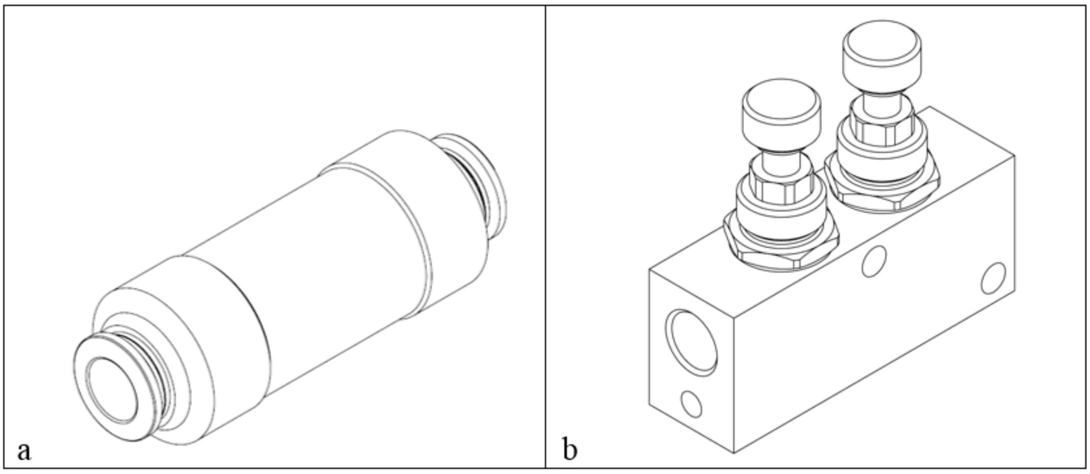

Figure 48. a) Check valve (Festo 2016f, p. 1), b) One way flow control valve (Festo 2016c, p. 1).

The flow control valve also functions in the same way as the check valve but it can also regulate the amount of flow of gas by adjusting the knurled screws. It is made up of wrought aluminum alloy and has a nominal flow rate of 0.003 m^3/s in flow control function and 175l/min in non-return direction. The operating pressure lies between 0.5 bar to 10 bar at an ambient temperature range from -20°C to 50°C. It weighs to 0.056 kg. The movement or speed of the cylinders can also be controlled using the flow control valve. (Festo 2016c, p. 1.)

4.3.5 Push in fittings, pipes and accessories

The push in fittings are used to connect the valves by one end thread mount and the other end push in. The push installation makes it easier to install the pneumatic lines and other valves. There are 3 different pipe sizes ∅8mm, ∅10 mm and ∅12mm. The complete gas circuits uses polyurethane (PUN) and perfluoralkoxyalkan (PFAN) tubes whereas the nitrogen circuit uses polyamide (PAN) tubes. (Festo 2016b, p. 4.)

The other accessories includes Y splitters that are used to split pneumatic lines from each other and sleeve connectors. Sleeve connectors are used instead of short tubing between the Y splitters. Mounting brackets and clips are installed to hold the tubes as gas flow during the working process can cause vibrations. The below figure 49 shows the accessories in the pneumatic system. (Festo 2016b, p. 2.)

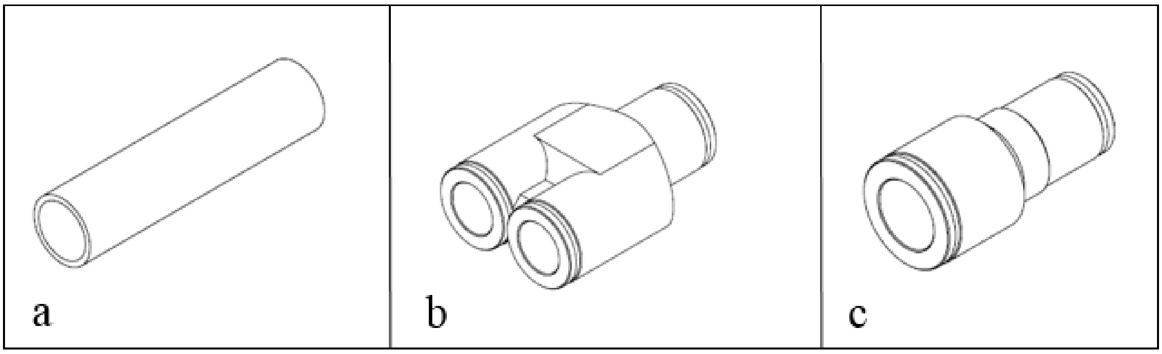

Figure 49. a) Tubes (Festo 2016b, p. 4), b) Y Splitter (Festo 2016k, p. 2) & c) push in fittings (Festo 2016d, p. 1).

5 LASER AND CONTROL UNIT

The laser and control unit is an integral part of the metal AM machine. It consists of the individual laser, the scanner head, the focussing unit, the controller, the interface monitor and the electrical unit. These components are assembled on the right chamber of the machine above the nitrogen unit.

The sliced 3D model to be printed is set as the input data and the laser beam tracks the scan data and begins melting the powder. The laser carries out the process layer by layer. The bed is already pre heated by sensors placed underneath it. The laser then melts the powder particle together and then the next layer is coated on the melted particles. The laser power is directly responsible for the amount of heat generated around the melted area. (Poprawe et al. 2015, p. 46.)

Productivity can be increase by having multiple beams and scanner heads. But these can have an effect on the pricing systems and complexity of the machine. The use of more amount of energy has a direct impact on total manufacturing costs. The scanning speed and scanning strategy of the scanner head is critical for the melting of powder particles. (Poprawe et al. 2015, p. 52.)

5.1 Laser unit

The laser existing in this machine is an Ytterbium fibre laser operating at 500 watt and is air cooled. The quality of beam is of excellent standard and is competitive in price. The mode of operation is a continuous wave laser. It has a wavelength of 1070±10 nm. The laser has a dimension of 448 mm x 497mm x 266mm and weighs more than 50 kg. The below figure 50 shows the laser unit. (IPG 2016.)

The air cooled laser system is suitable for the machine as it is void of water and supplements the system which is completely pneumatic and electrical. It consumes 1600 watt power and requires an electrical supply of 50 to 60 volts. The laser fibre cable is connected to the vario scan unit before it reaches the scanner head. (IPG 2016.)

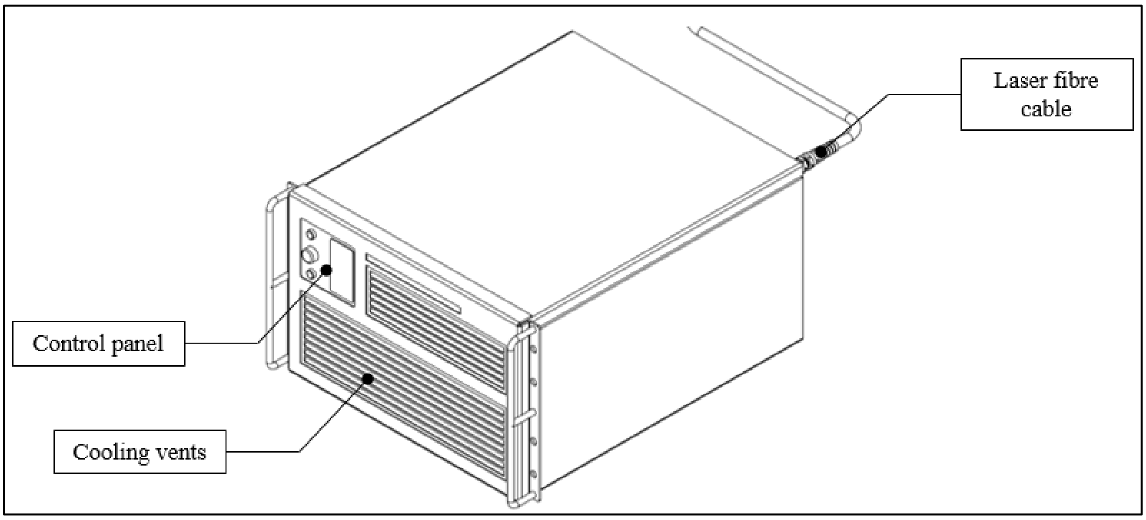

Figure 50. YLR – 500 – Air cooled (IPG 2016).

The scanner head used here is the intelliSCANIII 20 from scanlab which has high precision linearity and has good communication between the computer system and laser. For the working area of 400 x 400 m^2 and 70µm spot size this scanner head is suitable. It contains a 20 mm aperture lens and has a speed of 1.0 m/s. It weighs to 5.8 kg and has a typical scan angle of ±0.35 radian. The scanner head as an option to be air cooled or water cooled. The figure 51 below shows the scan head along with the varioSCAN unit. (Scanlab 2015a, p. 3.)

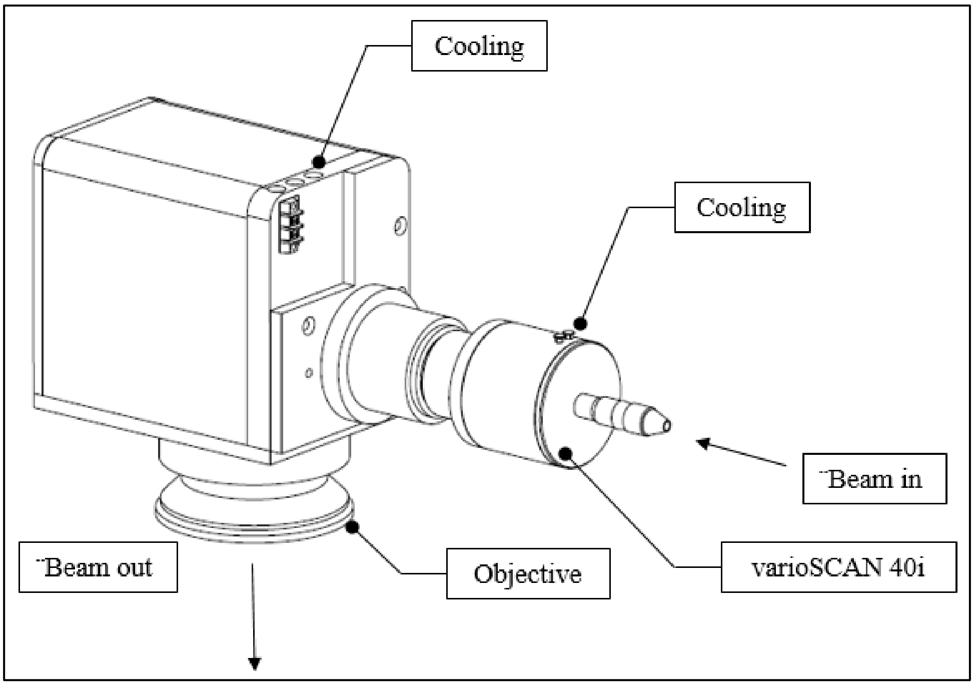

Figure 51. IntelliSCANIII 20 with varioSCAN 40i (Scanlab 2015a, p. 3; Scanlab 2015b, p. 2).

The scanner head also comes with a varioSCAN 40i. This enables the laser to be focused with greater precision along the optical axis including higher performance levels. The vario scan can change the 2d scan flat surfaces to a 3d axis scan system and costly flat faced specimens can be lowered using the vario scan. It contains a digital control interface and can be even controlled by 2d scan systems. It weighs about 500 to 600 g. (Scanlab 2015b, p. 2.)

5.2 PXLE 1085 controller

The controller unit is from National Instruments and the model is NI Pxle 1085. This is responsible for controlling all the process in the metal printing machine. It controls the powder feeding process, the printing process, the scanner input and the nitrogen unit. The controller has multiple slots that can be expanded to have multiple input and output signals. Figure 52 shows the controller placed next to the laser unit in the right side of the printing machine.

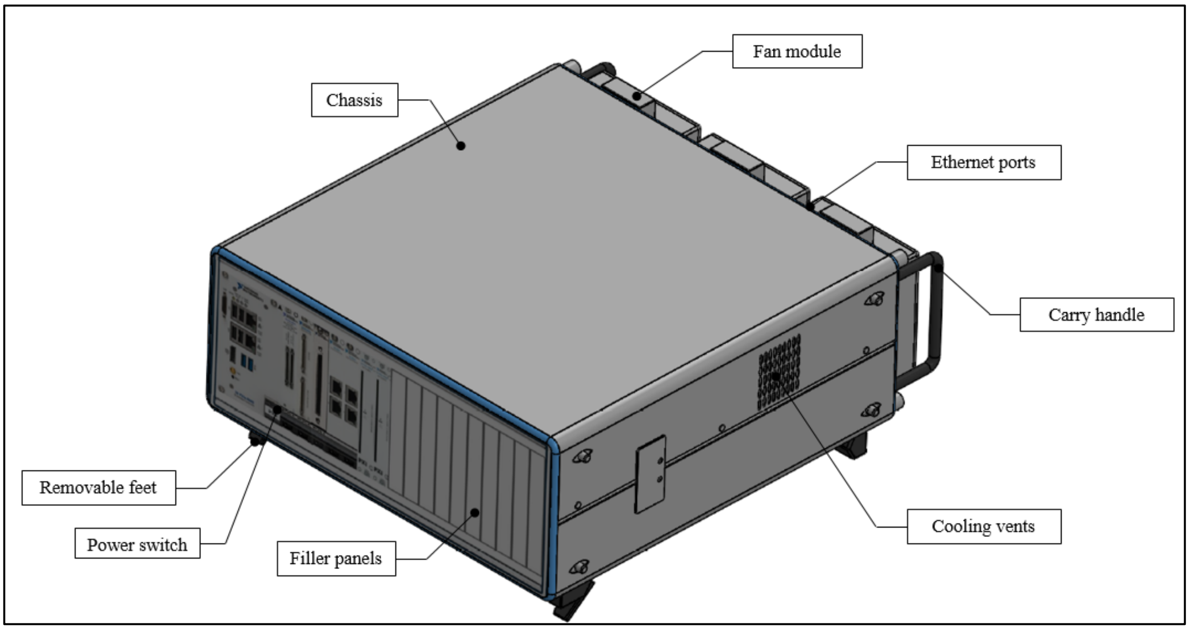

Figure 52. NI Pxle 1085 controller (National Instruments 2015, p. 12).

The controller has a 16 hybrid slot and works at an ambient temperature of 0°C to 50°C. It requires a total power of 925 W and has ethernet supply port and rear fan modules for cooling. It has a 25GB/s bandwidth and up to 8GB per slot, the slots being hybrid peripheral slots. The chassis has a module cooling system and has removable feet with an approximated dimension of 445.5 mm x 368.5 mm x 142.9 mm. The controller is placed on a free space and has removable connections accessibility for hardware repair and servicing. The power supply ports and fans are replaceable. (National Instruments 2015, p. 8.)

5.3 Computer peripheral

The computer peripheral consists of a monitor having a touch interface. It is assembled on the right side of the chamber with sheet metal and countersunk screws. The computer and control unit works in tandem to control the printing process of the machine. The input control code of the machine is fed into the monitor using LabVIEW. Below figure 53 shows the different parts of the touch screen computer.

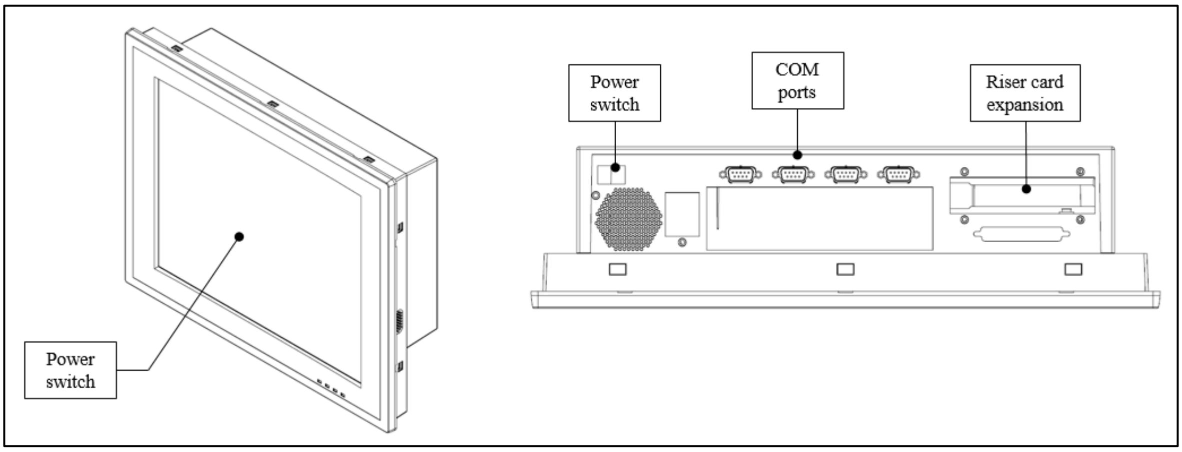

Figure 53. Advantech PC panel (Advantech 2016, p. 3).

The computer has a 17″ screen run by an intel core i5 processor and has a windows operating system. The resolution is 1280 x 1024 and has a LED panel having a built in H61 chipset. It can supports 6 Universal serial bus one along with 6 Communication ports. It requires a 100 – 240 v input and an output rating of 180 W. The LED display has a lifetime of 50,000 hours and touch screen of 36 million touches. It has a maximum internal storage of 16 GB. It has operating temperature between 0 and 50°C. The overall dimensions of the computer is 442 mm x 362 mm x 113.5 mm. (Advantech 2016, p. 1.)

5.4 Electrical unit

The electrical unit in this machine consist of the main electrical box and can be placed as many as required. The machine at this stage is void of electrical connections. The design is limited without the wiring, harnessing of the electrical system. Below figure 54 shows an electrical box placed in the machine.

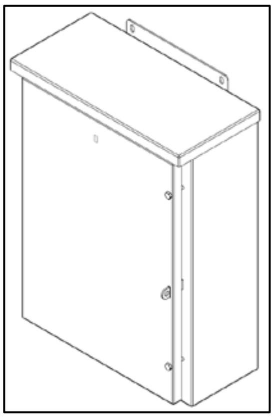

Figure 54. Electrical box.

6 WORKING PROCESS

The process of the machine begins with the input of stereolithographic (STL) files from a CAD or CAD integrated slicing software. The building plate is initially heated to 80°C and is now ready for laying of powder layer. The powder blade moves in a direction from left to right spreading a layer of metallic powder particle over the building plate. The laser then melts the powder according to the scan data. The building plate is lowered by the electro mechanical cylinder. The powder blade then moves from right to left laying another layer of powder. The layer thickness can vary according to the input specifications. This process of blade movement occurs repeatedly until the part is printed.

The powder blade gets a continuous supply of powder on a regular interval as it reaches its start point on the left. The powder from the powder chamber drops into the blade from a height of 3 mm. Once the metallic part is printed the part slowly moves from the building chamber into the built chamber. This happens gradually due to the lowering of the electro mechanical cylinder movement downwards.

The built chamber is tightly closed by the top door of the building chamber. A vacuum is created in the powder tank. The valve between the built chamber and powder tank is closed during the vacuum creation. Once the vacuum is created compressed air is released into the built chamber at high velocity and the valve is opened. Due to the pressure drop the powder from the built chamber escapes into the powder tank and the metallic printed part is ready to be taken out along with the building plate.

The powder pump sucks the powder upward and transfers it to the sieving station where the unfiltered particles are collected in a separate tank and the filtered powder is sent back to the top powder chamber in the building chamber. A vacuum blower supplements the flow of powder particles along the route.

When the powder removal and filtering processing happens simultaneously the melted part is taken out of the chamber. The pneumatic powered door opens and magnetic plates drags the building plate outwards using an AC motor. The building plate and workpiece is brought to the ball transfer unit. The ball transfer unit offsets the plate and transfers it to the conveyor in which it is carried to the left side. New building plate is then loaded onto the building platform and is taken upwards by the electromechanical cylinder for the whole process to begin again. Below figure 55 shows the working process of the machine.

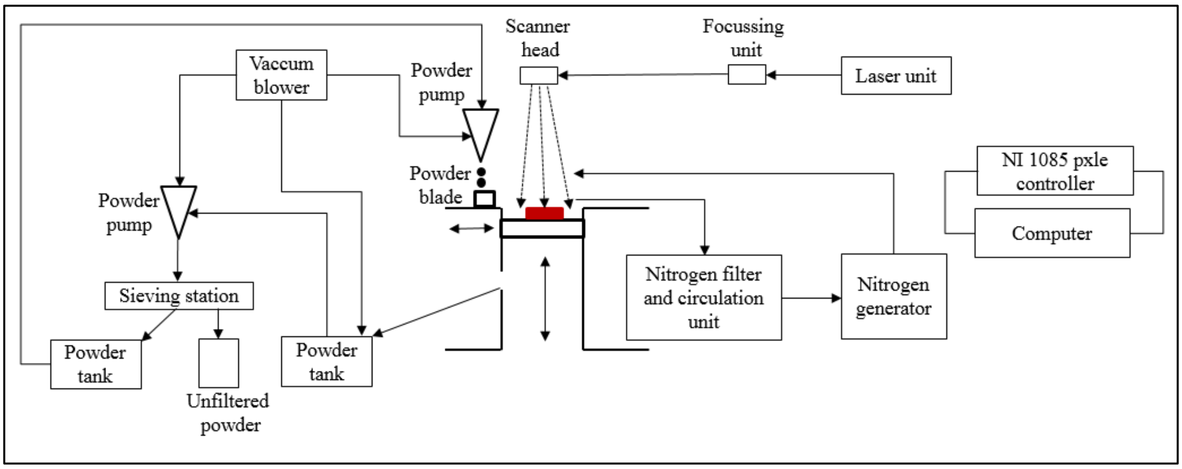

Figure 55. Working process of the machine.

7 FURTHER RESEARCH

Further research can be carried out on building additional modules for heating, cooling and post processing applications of the work specimens. Hardness of specimens can be controlled by heating and cooling at different speeds. A module can also be attached for forming and densifying where heat is supplied in a closed chamber with high pressure of inert gas to remove voids and join sintered metal particles in the specimen.

Electroplating and painting are another 2 process than can be included in the machine which is required for finished specimens. Lasers used for coloring process can be installed in the machine to carry out painting and engraving on finished specimens. Post processing applications like milling, cutting, surface finishing and polishing can be integrated to the metal AM machine. The increase of modules mean large working space is required for the installation of the machine which can be challenging for smaller companies.

The different choice of materials like aluminum, low alloy steels, nickel alloys, cobalt alloys being able to be printed by a single machine will boost the chances of the metal AM machine in the global market. Addition of multiple lasers and moving scanner head can increase the build area but incurred with it are the manufacturing costs. Research into different gases that are optimal for the varied material choice will be an opportunity for the machine to become unique. Powder printing of different material layer over layer in a single component is also a technique the machine can adopt in the future.

The removal of the workpiece individually from the building plate by installing cutters and grinders will be a boon for the AM machine. The supports structures removal and cleaning of the building plate within the machine itself will be an advantage in the future. They are time consuming process now as they are transported to different stations using robots. Testing needs to be carried out in this machine to check if all the components selected for this machine is optimum.

8 CONCLUSION

This report gives a detailed description of the main components associated to the new metal AM machine that can be built. The metal AM machine to be built is of competitive quality and has novel and different mechanisms for powder coating, powder removal and removal of the building work plate along with the finished workpiece. The machine is designed from scratch and has completely new design for most of the components. The prototype phase will undergo testing and new design changes could be adopted later in the machine.

The powder feeding and removal process is a new mechanism and is suitable to patent. There are similar mechanisms adopted by different metal AM machine companies in the market but in theory this shows to be efficient and has an optimum design. Most of the companies focus on the powder removal process in their new machines and this machine is already established having the process.

The removal of the finished workpiece without manual handling of the powder is another field the markets are trying to conquer and this machine already has this installed in its new design. The manual handling of the powder can be hazardous to the operator and it also is a time consuming process which the machine solves the problem.

The pricing strategy of the machine is optimal as many industries begin to purchase AM metal machines. Companies have brought down the price of the metal AM machines due to low cost laser and scanner heads. This gives buyers a lot of options and range to choose from. The metal AM machine can become the first machine to be built in Finland and grow in the market.

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