Development of Laser-Based Powder Bed Additive Manufacturing machine for metals

Dual Degree Project Report II

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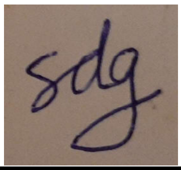

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Abstract

Additive manufacturing has gained significant attention to industries and researchers as it allows complexities, higher surface finish, less waste generation. Single machine is required for end to end solution e.g. currently a group of machines and processes i.e. casting, lathe, milling, grinding is used to make a product. Powder Bed Fusion (PBF) is one of the process using which additive manufacturing is done. It provides higher cooling rate and better surface finish. PBF is done using either laser or electron beam to fuse materials by providing high energy to melt the powder.

This project is based on developing a laser-based powder bed fusion machine for metals. A powder of metal is spread as a thin layer on a platform. Then a laser of high power melts the powder and leads to fusion among them. After the fusion process, the platform is moved downwards as much as the layer thickness. This procedure is repeated till the final product is fabricated. The particle diameter should be less to achieve smoothness, less power of laser would be enough for melting of powder and a thinner layer could be achieved. If the particle diameter is uniform then properties of material obtained would be uniform but will consist of voids whereas if the size is between a range then void formation would be less as powder of smaller size would go into empty spaces. This would increase density and hence, strength of material.

For design of machine steel (7.8 g/cm^3) powder is used as it is dense and cheap as compared to other powders e.g. titanium (4.4 g/cm^3) and aluminium (2.7 g/cm^3) as maximum loading will be when a dense powder is used. So, if the system can hold loading due to steel then it will be suitable for other powders also. Research and development have been done mostly on polymers and less has been done on metals. For metals, PBF machine has been developed for smaller dimensions and thickness of 100 microns has been tried to achieve. But for industrial applications where high accuracy is required, 100 microns thickness needs to be reduced. To cater this issue, in this project the aim is to achieve a minimum layer thickness of 25 microns. The machine has been tried to build such that it has a bed size of 400mm*400mm and can reach up to a height of 400mm and layer thickness can go lowest up to 25 microns. This makes the machine novel in comparison to other PBF machines available in market. Lesser layer thickness will increase the surface finish of the product obtained with higher accuracy, better tolerance and denser which is essential in PBF process to provide higher strength.

Chapter 1

Introduction

1.1 About Additive Manufacturing (AM)

Additive manufacturing is the technology of building object layer by layer commonly in precise geometric shapes[1]. It is also capable of manufacturing complicated parts than subtractive methods[2]. Additive manufacturing offers lot of advantages over traditional manufacturing methods including rapid manufacturing, tooling, and rapid prototyping[2]. Additive manufacturing has wide scale application specially in aerospace and medical areas due to its capability of generating high performance metal parts and its ability to fabricate anatomical parts with scanned data[3]. There are a lot of additive manufacturing techniques including VAT photopolymerization, material jetting, material extrusion, powder bed fusion, binder jetting, direct energy deposition, and sheet lamination[4] differing on mechanism of manufacturing.

PBF technology offers various control parameters like hatch, scan velocity, laser power, layer thickness and build direction which influence the microstructure formed and hence the mechanical properties.

1.2 Common technologies of AM

There are lot of different mechanism for adding material layer by layer and then further solidifying and cure parts. Some of the following are listed below.

1.2.1 VAT Photo-polymerisation

In Vat polymerisation a liquid photo polymer resin is used to make model layer by layer. Generally, UV light is used for curing the model so formed. In this build material is liquid unlike powder in all other case. The liquid on top is cured then the platform moves downward in Y direction. Hardening of liquid takes place at region where it comes in contact with light. The process of curing takes place according to the geometry to be manufactured. In this way part is constructed layer by layer. The process of curing by UV light is called photo polymerization. The figure below demonstrates the photo polymerization process.

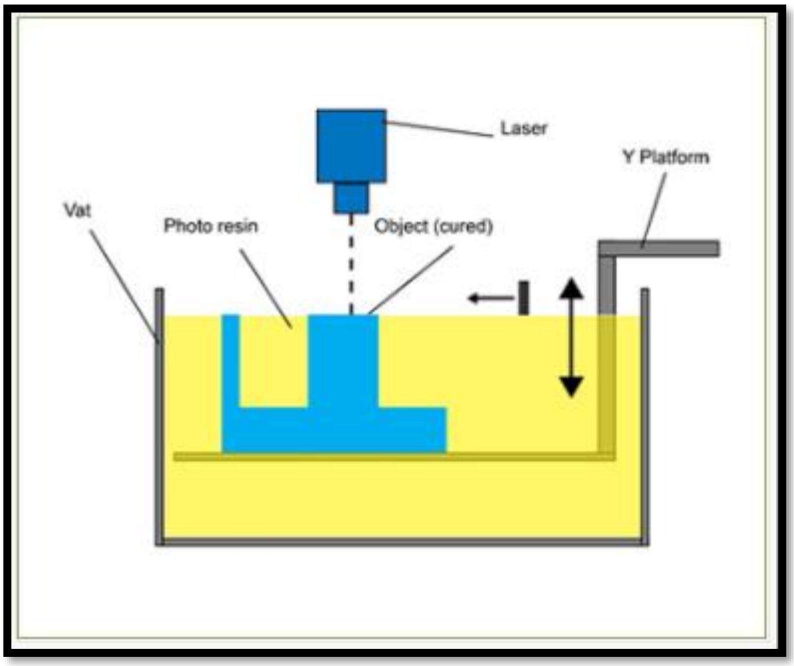


Figure 1: Apparatus for VAT Photo polymerization[5]

1.2.2 Material Jetting

As the name suggest in this method material in form of drop is deposited on to platform via nozzle. This nozzle moves in XY plane and provides drop on demand to build the object. After first layer is created these drops are allowed to cool and solidify. Then the subsequent layers are also made in same way . After the part is fully manufactured then the material which was being used as support for the process is removed and hence the object to be made is ready.

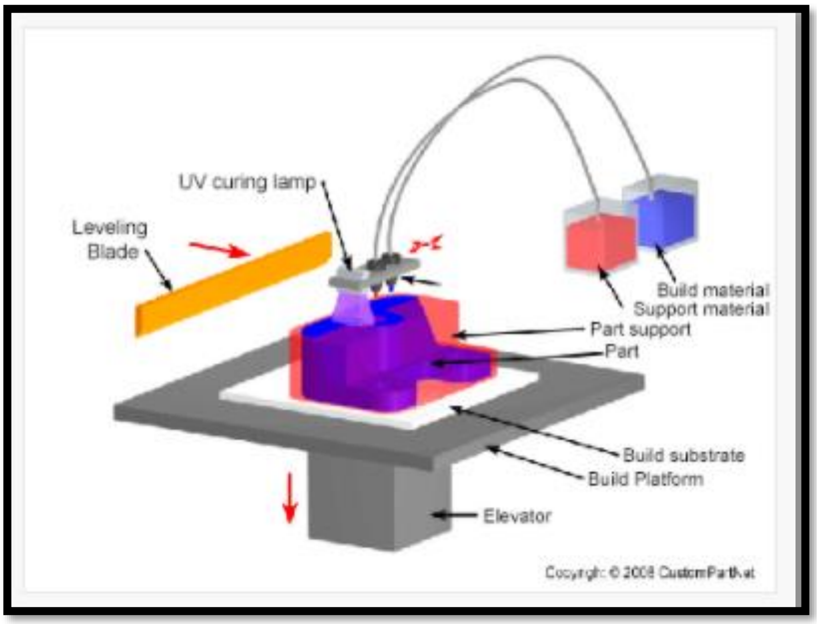


Figure 2: Apparatus for Material Jetting[6]

1.2.3 Binder Jetting

In this technology the printer used has both binder (generally liquid) and powder. The layers of powder and adhesive binder is deposited alternately to hold the layers of powder together, similar to other technology the depositor moves in XY plane and platform moves in Z in order to manufacture part layer by layer. Apart from the time taken by manufacturing post processing of parts manufactured by this process also takes decent amount of time.

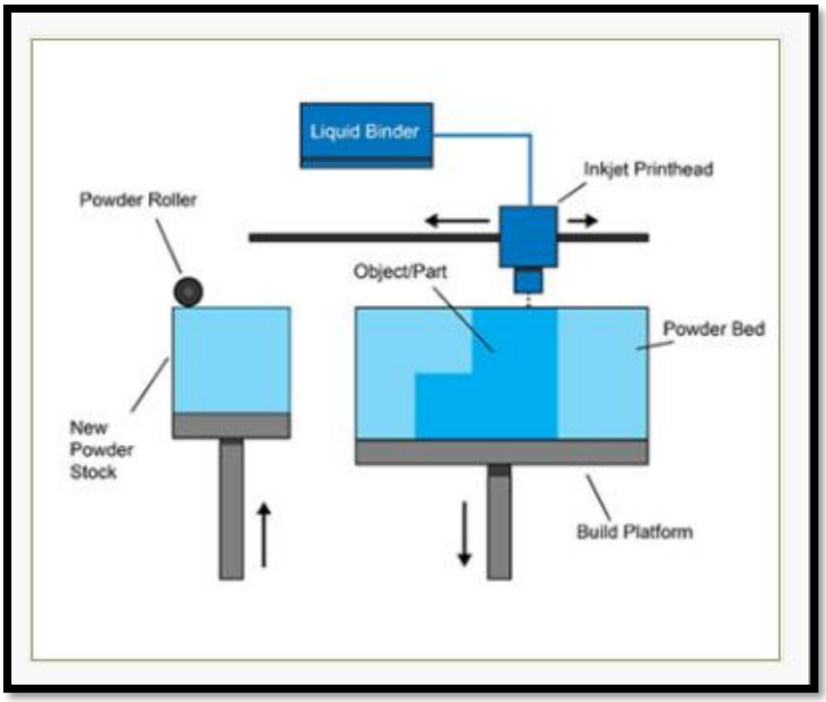


Figure 3: Apparatus for Binder Jetting[7]

1.2.4 Material Extrusion

In this method material is heated and drawn through nozzle which then is deposited layer by layer. The nozzle can move in XY plane and develops layer geometry while platform moves in Z for development of height of object. This method is used in most of 3D printers. It is different from other methods in respect that the material is drawn from nozzle at constant pressure. Material among the layer is bonded with chemical called binders which are fed through spools.

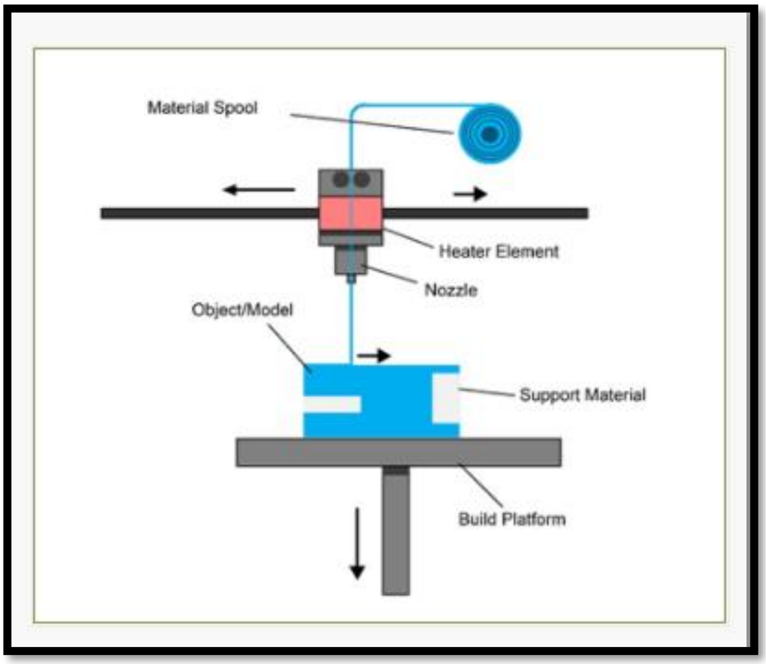


Figure 4: Apparatus for Material Extrusion[8]

1.2.5 Powder Bed Fusion

In this technique first, the powder is spread on the platform then by using electron beam, laser beam etc the powder is sintered. Then next layer of powder is added and sintered. This process is repeated until whole of part is made. Due to unmelted powders in between this method leads to development of porosity. The machines based on Direct metal laser sintering (DMLS), Electron beam melting (EBM), and Selective laser sintering (SLS) use this method for forming parts.

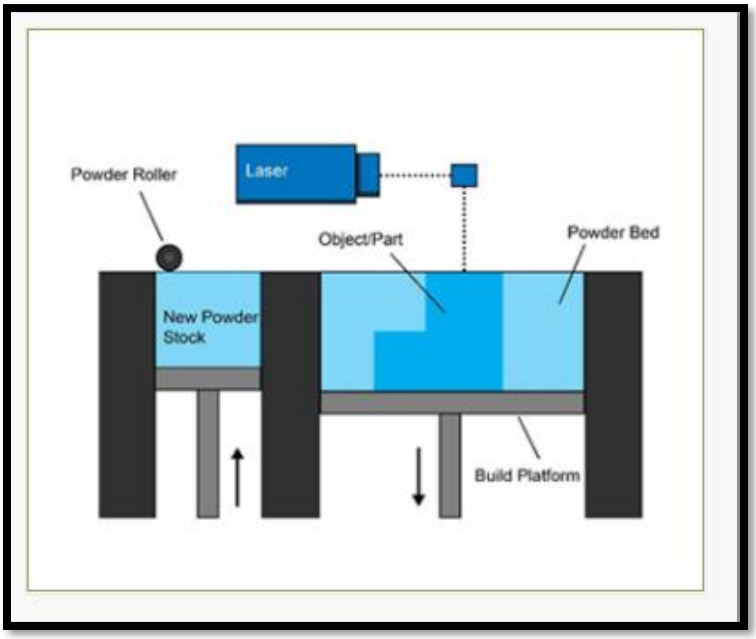


Figure 5: Apparatus for Powder Bed Fusion[9]

1.2.6 Sheet Lamination

In this method the material in form of ribbon or paper is used which is supplied by material spool. Then the next layer of material is bonded to first layer by ultrasonic welding process (Ultrasonic Additive Manufacturing) or by using adhesive (Laminated object manufacturing). Then after deposition required material is cut in shape required using lasers. Then second layer is added which is bonded and positioned and then cut with laser. This process continues until the part is made.

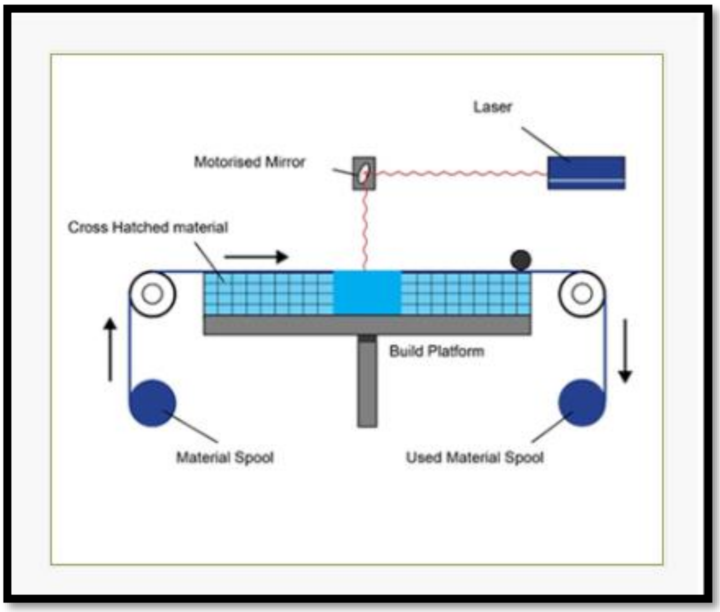


Figure 6: Apparatus for Sheet Lamination[10]

Chapter 2

Literature Review

K.R. Bakshi et al.[11] did a review on Selective Laser Sintering (SLS) and concluded that it is the most flexible process as it provides manufacturing of complex shapes and use of different materials. It is difficult to automate and control, still as it provides a large number of parameters can provide good quality of products. S. Singh et al.[12] worked on investigating dimensional accuracy and on mechanical properties of parts produced by SLS. They found that the major reason for inaccuracy is because of shrinkage of metals at higher temperature which is not uniform. Shrinkage is more where temperature is higher and vice-versa. Also, shrinkage is sometimes constrained by the powder on previous layer. Apart from metals, ABS (Acrylonitrile Butadiene Styrene), polycarbonates, polyamides[13–17], polyethylene[18,19], or ferrielectric polyvinylidene fluorides[20] and nylon are used in SLS[21].

AM is considered to be done in three phases: design phase, manufacturing phase and testing phase. STL file format is the most used format for AM processes.

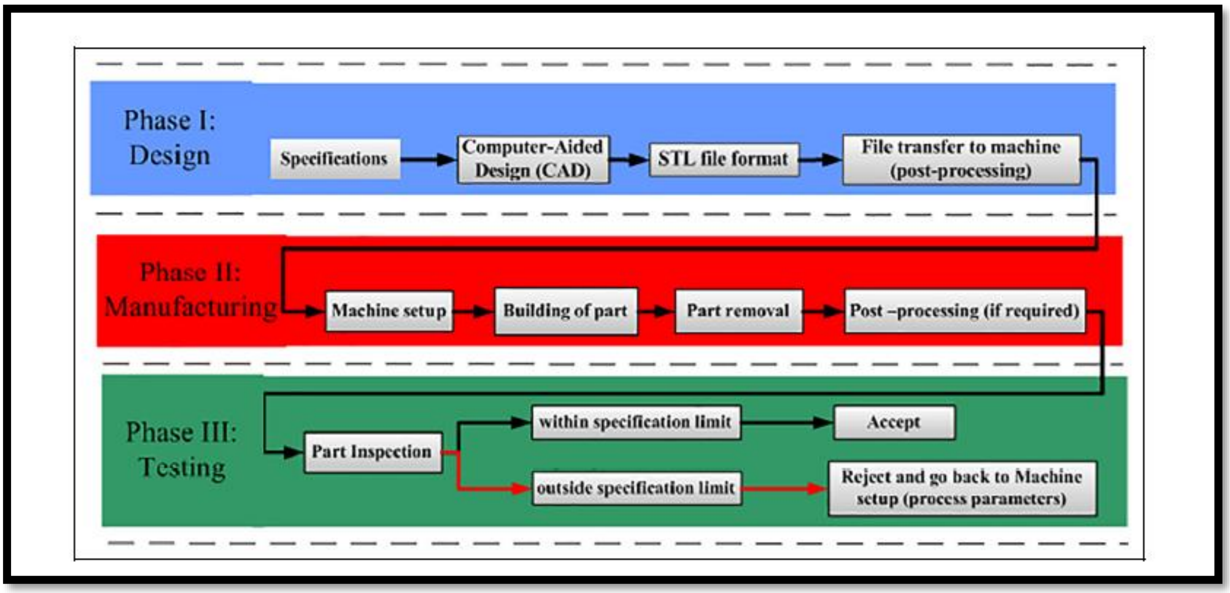


Figure 7: Phases of additive manufacturing[3]

The mechanical properties achieved are same to those produced through conventional manufacturing. Density up to 99.9% can be achieved in laser-based PBF[22]. One of the disadvantages of PBF is that a lot of residual stresses are generated and larger deformations are there. These residual stresses lead to thermal cracks. It is difficult to have uniform quality in PBF process during formation process, thus causing varying viscosity within the part[23].

S. Sun et al.[24] worked on different process parameters to optimize the process for powder bed fusion. The parameters they considered were based on the processes i.e. laser-related, scan-related, powder-related and temperature-related. In laser: laser power, wavelength, spot size, pulse duration, pulse frequency; in scanner: scanning speed and scanning pattern; in powder: particle size and distribution, particle shape, powder bed density, layer thickness and material properties; in temperature: powder feeder temperature, powder bed temperature and temperature uniformity are considered. They used a hopper to deliver the powder whereas N.K. Roy et al.[25] lifted the feed cartridge to a controlled height.

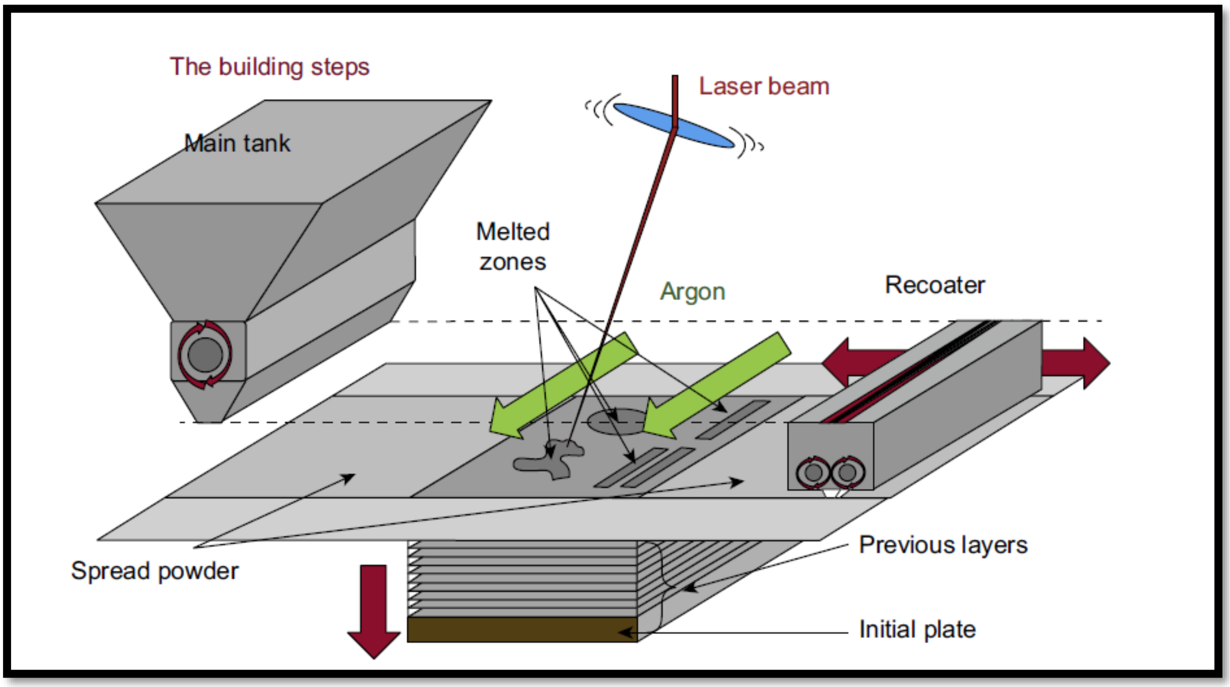


Figure 8: Complete assembly of laser-based PBF used by S. Sun[24]

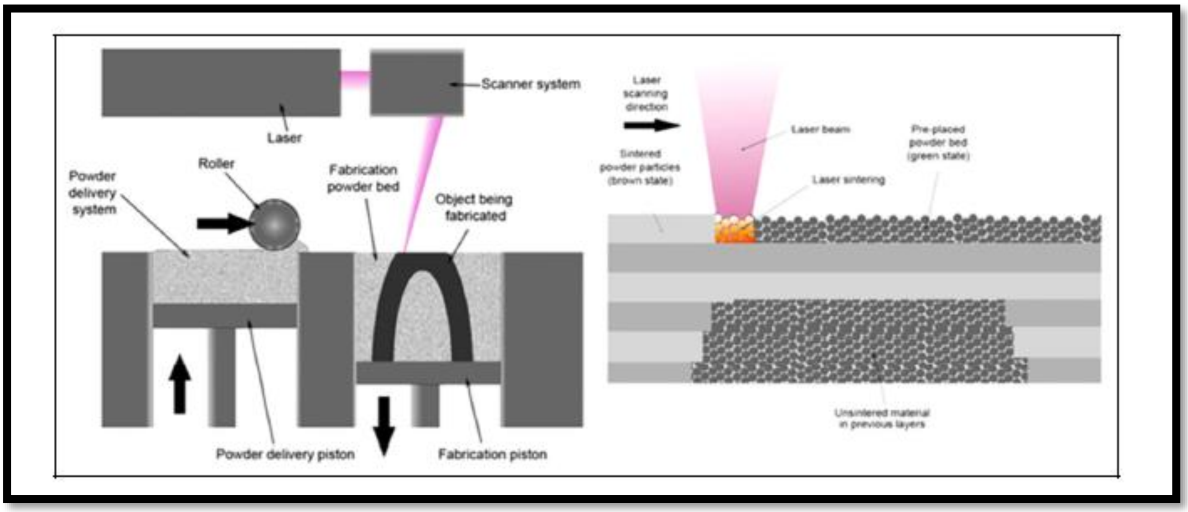


Figure 9: Cartridge lifting mechanism to deliver the powder[3]

A. Nazarov et al. worked on designing a setup for SLS of high temperature polymer materials with the alignment control system of layer deposition[26]. They designed SLS equipment for high temperature polymers. They provided multi-circuits heating systems and also worked on protecting the devices of the setup from thermal effects.

P. Regenfuss et al.[27] worked on improving the resolution of laser sintering for metal and ceramic powder. They provided tight localization of the sintering for high resolution. They also observed that rapid heating, the generation of plasma flume, and rapid cooling have proved to be advantageous for metal sintering.

Based on the literature review, not much has been done on large scale metal sintering. Most of the PBF experiments are either based on polymers or are for smaller dimensions of metal. The challenges for large scale are mainly because as the size increases weight also increases, so to move such a heavy system with high precision is difficult. In this project, an attempt is made to make a machine which can manufacture objects up to 400mm*400mm*400mm.

After building up the machine, proper parameters have to be given like beam diameter, scanning speed, laser power, layer thickness to allow sintering to be done with optimum quality of product being produced. Many researchers have worked on optimizing parameters for sintering process and have found how the quality of product obtained depends upon the parameters given to the setup. A. Simchi[28] tried different powders with direct laser sintering process and studied their densification and microstructural evolution. According to him: i) Increasing energy input and decreasing scanning speed will increase density; results shows that density is proportional to laser power/scan rate; ii) Increasing layer thickness and spacing decreases the density; iii) At high energy inputs delamination of sintered layer and formation of large cracks are feasible which may lead to lower density; iv) Material composition also plays a major role in increasing density: increasing the composition of carbon, phosphorous and copper enhances the sintering rate of iron powder at given fabrication rate; finer powder with larger surface area have a higher sintering rate; v) At larger layer thickness (0.2mm), the effect of particle size is more noticeable at lower energy inputs; at lesser layer thickness (0.05mm), the effect of particle size is more pronounced at higher energy inputs; vi) At lower scan rates the material has tendency to boil too; vii) The solidification shrinkage and surface tension effect results in formation of large inter-agglomeration pores; the high thermal gradients are accompanied by high thermal stresses which does not allow 100% densification even at high laser energy; viii) Sintering rate is linearly proportional to P/(wh) where P is laser power, w is layer thickness, h is scan line spacing; ix) Minimum attainable porosity depends upon material properties and varies between 0.02-0.3; x) The formation of oxide layer on the surface of powder particles significantly increases the absorption rate of CO2 laser radiation. This changes the temperature-time history of sintering and increases the melt volume, allowing surface tension become more dominant. Another concern is the liquid metal surface tension, which influences the wetting angle between the solid and the liquid phases that can disrupt bonding between rastered lines and individual layers. Therefore, the amount of oxygen present during the heating, melting, and fusion of metal powders in the laser sintering process should influence the densification and the attendant microstructural features.

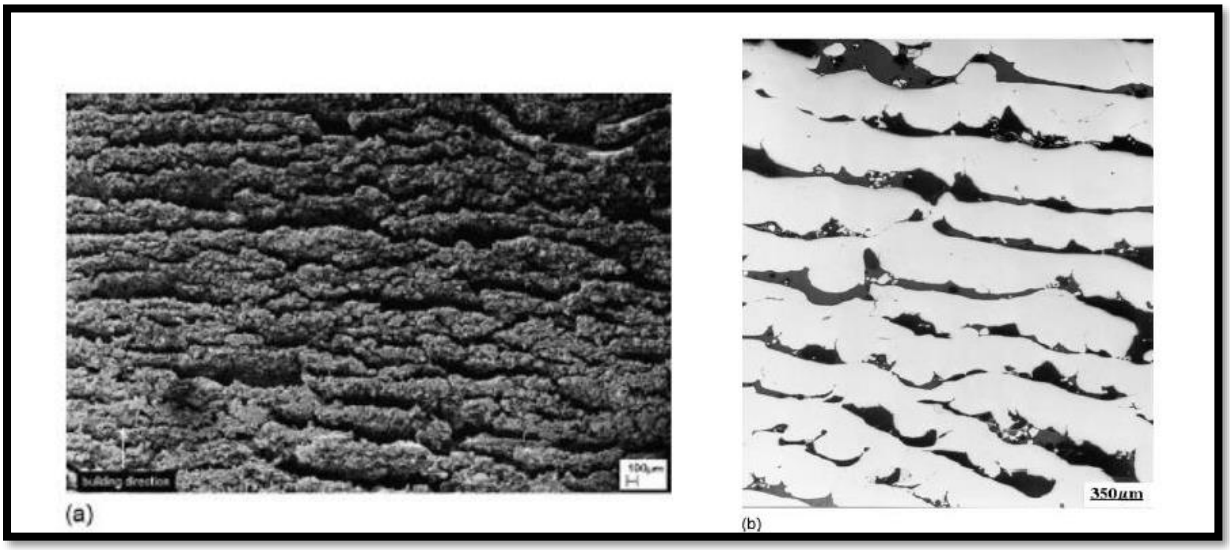
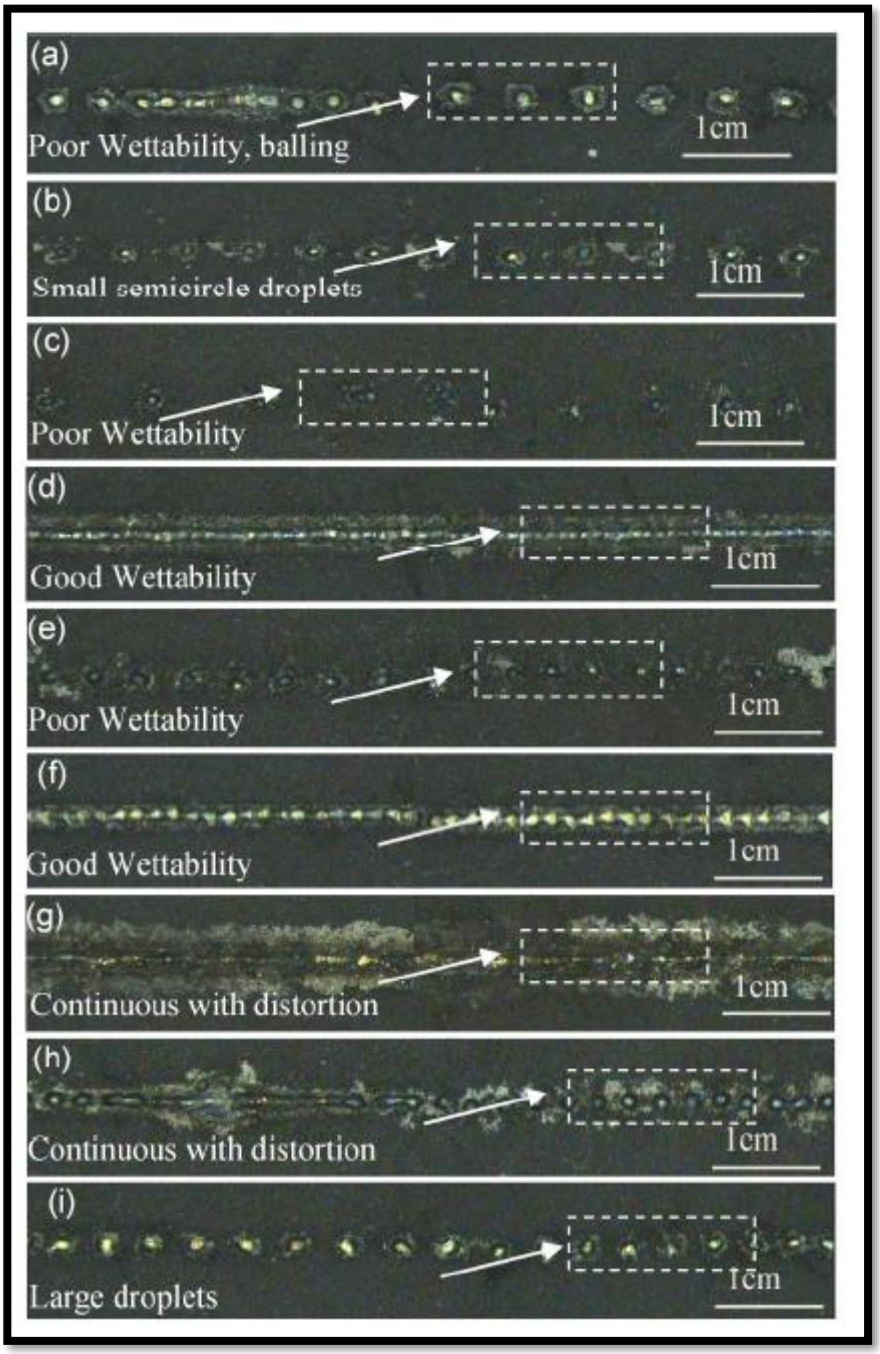


Figure 10: Delamination of sintered layer (a) and formation of large horizontal cracks (b) at higher energy inputs[28]

Kurian et al.[29] studied the effects of process parameters on wetting phenomena and interfacial energy during laser melting of stainless-steel powder. They found out that at lower energy density melting does not occur properly which increases contact angle and causes distortion leading to poor wettability. During high energy input or low scanning speed, time to absorb energy is more which allows larger degree of melting and hence good wettability.

From Figure 11, it can be inferred that good wettability can be obtained for 316L stainless steel powder at 150W laser power, 2.4 m/min scanning rate and 400 microns layer thickness.



(a) P= 100 W; V= 2.4 m/min; d= 300 µm.
(b) P= 100 W; V= 8.4 m/min; d= 400 µm.
(c) P= 100 W; V= 12 m/min; d= 500 µm.
(d) P= 150 W; V= 2.4 m/min; d= 400 µm.
(e) P= 150 W; V= 8.4 m/min; d= 500 µm.
(f) P= 150 W; V= 12 m/min; d= 300 µm.
(g) P= 200 W; V= 2.4 m/min; d= 500 µm.
(h) P= 200 W; V= 8.4 m/min; d= 300 µm
(i) P= 200 W; V= 12 m/min; d= 400 µm.

Figure 11: Macrograph of Single-track formation of SS316L powder on SS316L substrate[29]

Chapter 3

Machine Development

3.1 Parts of machine

In the powder bed fusion machine, first the layer needs to be delivered out on the platform. Then the powder has to be spread, followed by the use of the roller to break the agglomerates. After that, the fusion is done and the platform moves vertically downwards. Then the cycle repeats till the final product is formed.

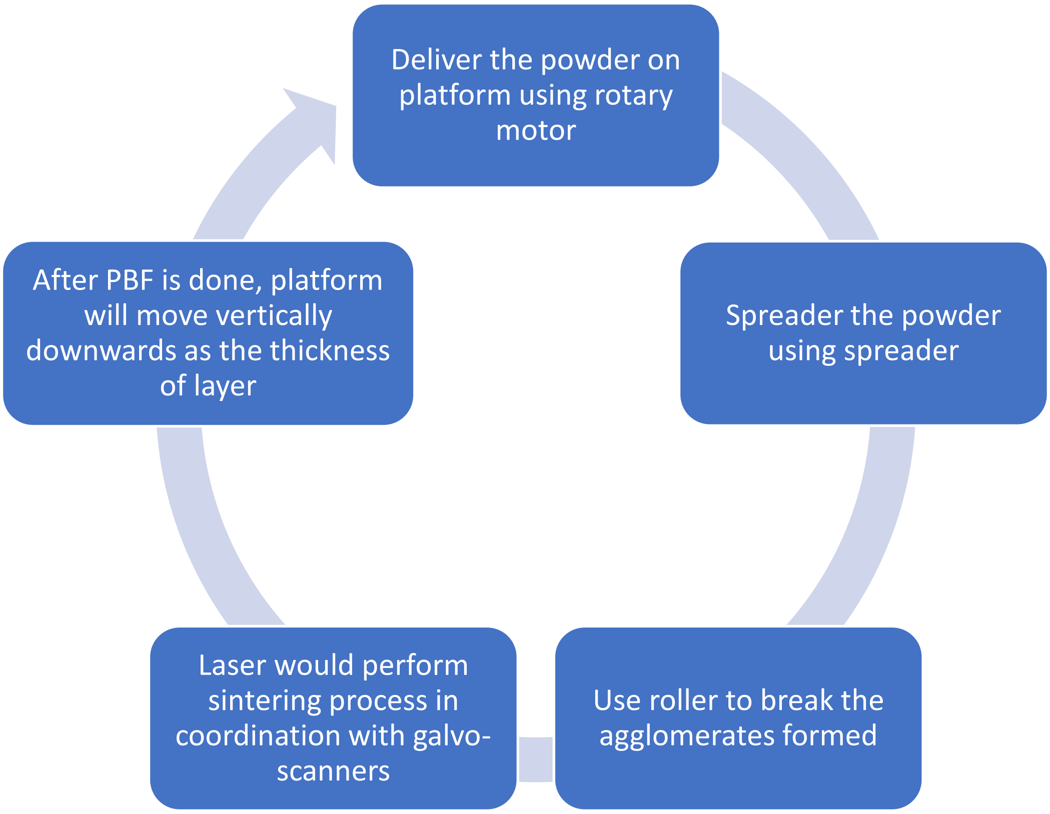


Figure 12: Complete cycle of PBF

In Figure 13, the second column consist of processes involved and in the third column components required to achieve the processes are involved. The machine would be having the following processes: Melting of powder, vertical motion of platform on which fusion is done and the mechanism used to deliver and spread the powder.

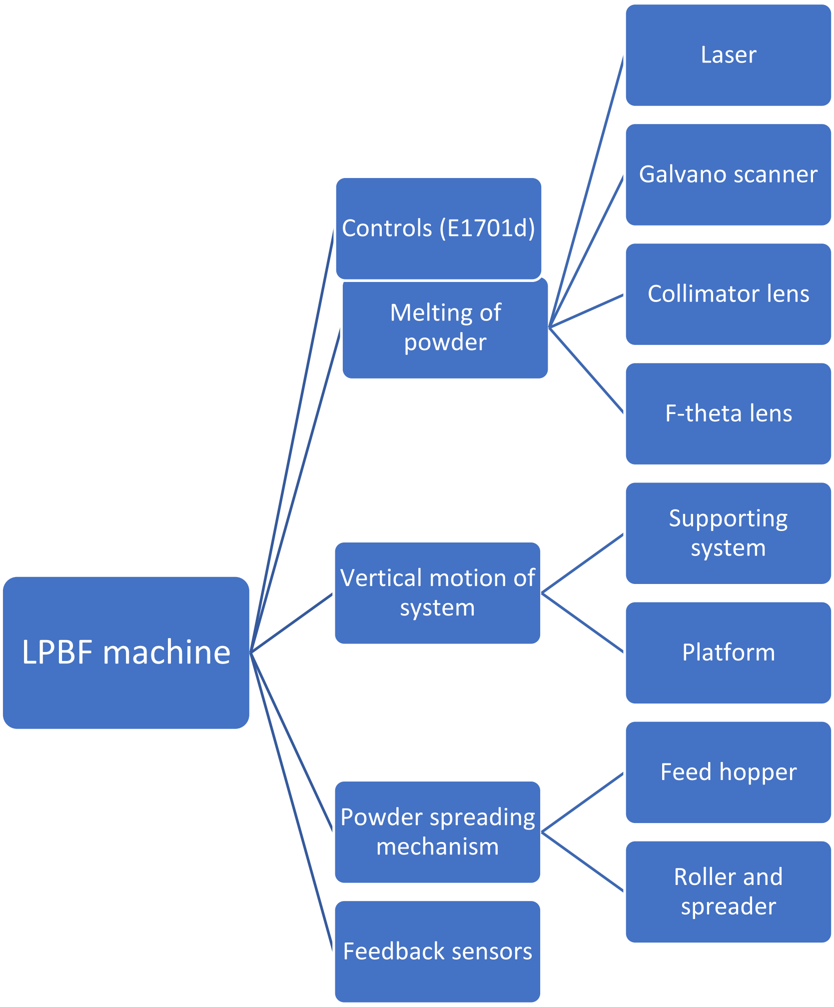


Figure 13: Flowchart for PBF machine

3.2 Controls (E1701d)

Laser, galvo-scanner, vertical motion system, and powder spreading mechanism have to be given commands one after the another. The process would be as follows till complete fusion is done. E1701d controller has its software, i.e., BeamConstruct, in which the user has to draw the shape or insert the 3D model and feed the parameters for motors and laser. E1701d can operate up to 4 motors, and as per the requirement, each motor for the feed hopper, spreader, roller, and vertical motion of the platform is required. It also has eight digital input pins, which can be used for referencing motors whenever they reach their home position.

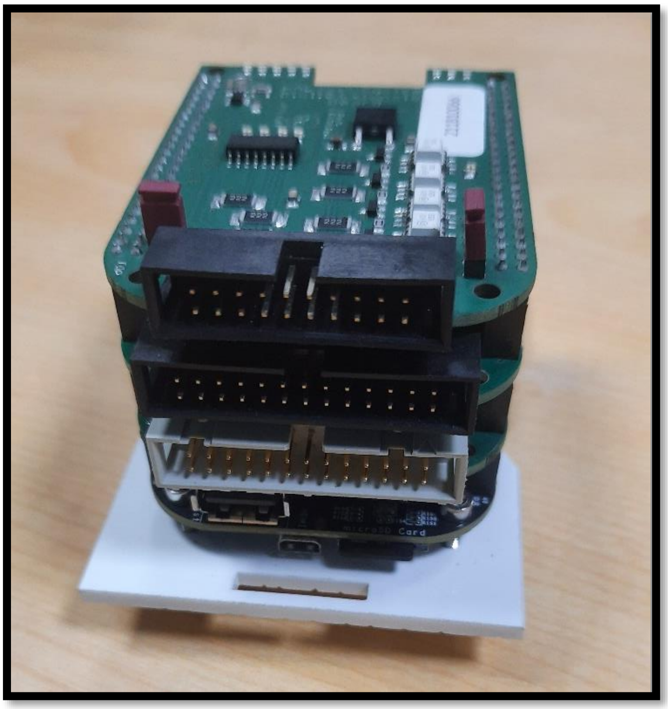


Figure 14: E1701d controller

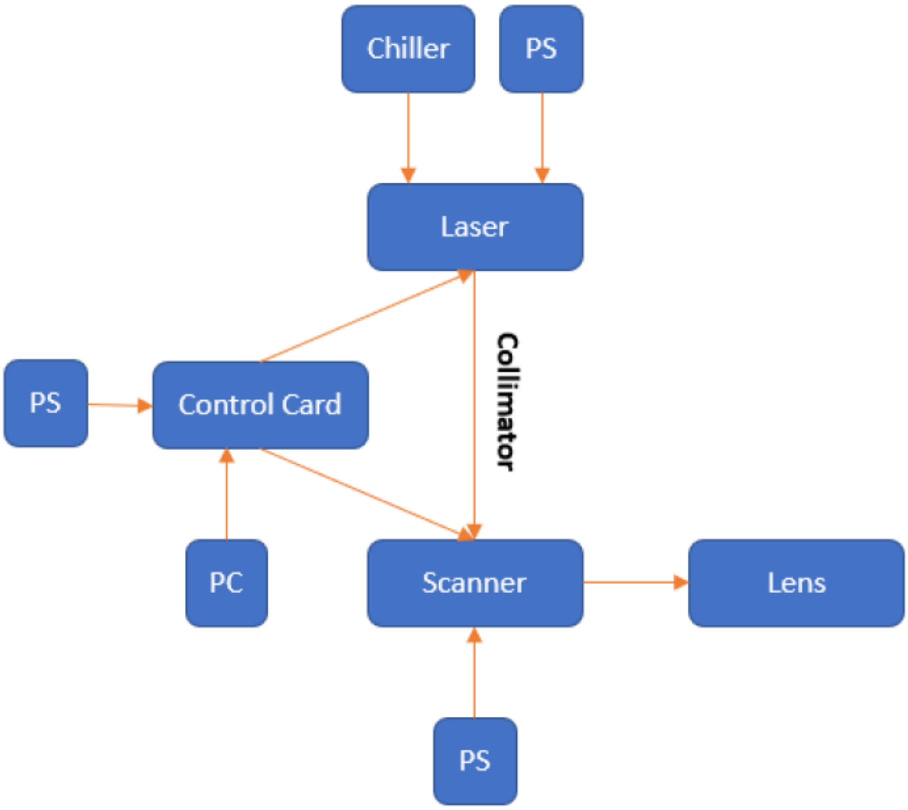


Figure 15: Flowchart for connection of controller with laser and galvo-scanner (PS: Power supply, control card: E1701d, PC: Personal Computer)

3.3 Melting of powder

Figure 16: Path of propagation of laser

3.3.1 Laser

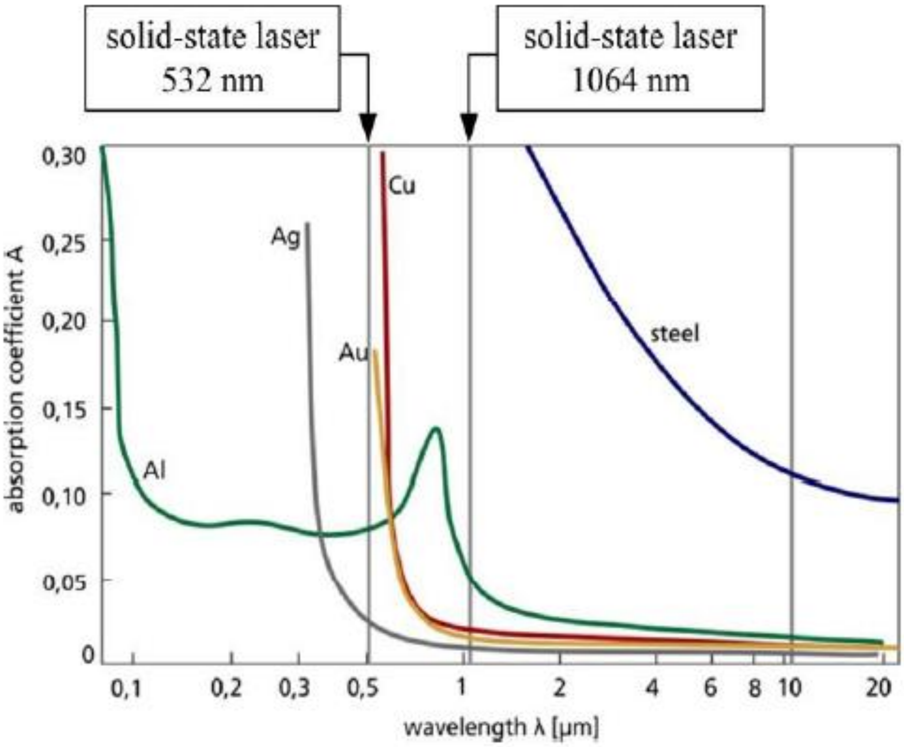


Figure 17: Absorption coefficient of different metals at different wavelengths[30]

From Figure 17, it is clear that steel has the highest absorption coefficient near lasers at 1064nm wavelength. A 500W continuous wave fiber laser is used, emitting laser of wavelength 1080nm (1075-1085nm) and operating at 220 VAC. It is connected to a water chiller for cooling and keeping the water temperature between 26-28°C.

Laser can be controlled in two ways: either using its own software, which is connected via RS232 connector to PC, or an external connector connected to the controller. The RS232 connector is just for testing of laser.

Figure 18: 500W fibre CW laser

Table 1: CTRL interface design

CTRL INTERFACE PIN	WIRE COLOR	FUNCTION DESCRIPTION	REMARK
1	Red	Emission enable input (positive)+	24VDC high level voltage valid
2	Red and White	Emission enable input (negative)-	
3	Black	Modulation input (positive)	24VDC high level voltage valid
4	Black and white	Modulation input (negative)	
5	Yellow	External laser output (positive)	24VDC high-level voltage valid (This function is same with auto switch START)
6	Black and yellow	External laser output (negative)	
7	Green	DA(0-10V) input (positive)	analog signal, control output power %
8	Green and white	DA(0-10V) input (negative)	
9	Brown	Fault output 1	

10	Brown and white	Fault output 2	Fault output 1 and 2 off when alarm on
11	Blue	NC	
12	Blue and white	NC	

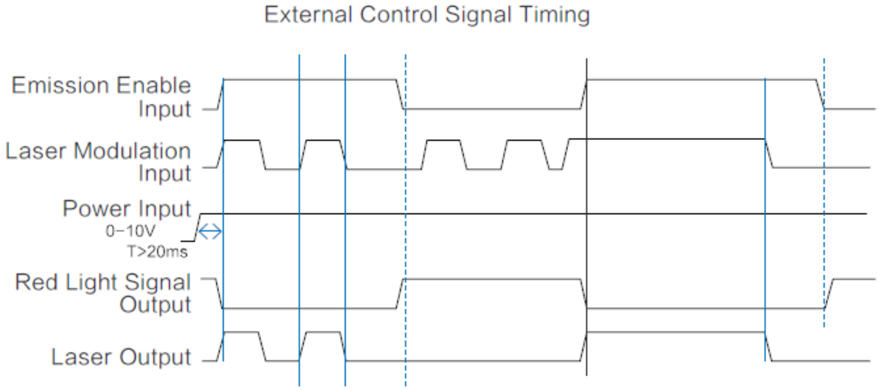


Figure 19: Operation of laser

Table 2: Pin configuration of LP8 extension board to control laser

Upper Row Of Pins	Signal	Voltage	Remarks	Lower Row Of Pins	Signal	Voltage	Remarks
1	LP8_0	CMOS, 0/5V, max 8 mA		2	GND	GND	
3	LP8_1	CMOS, 0/5V, max 8 mA		4			
5	LP8_2	CMOS, 0/5V, max 8 mA		6	5V	5V	
7	LP8_3	CMOS, 0/5V, max 8 mA		8	MO	CMOS, 0/5V, max 8 mA	Main Oscillator
9	LP8_4	CMOS, 0/5V, max 8 mA		10	AOut0	0..5V, max 15 mA	Analogue output
11	LP8_5	CMOS, 0/5V, max 8 mA		12			
13	LP8_6	CMOS, 0/5V, max 8 mA		14			
15	LP8_7	CMOS, 0/5V, max 8 mA		16			
17	LP8 Latch	CMOS, 0/5V, max 8 mA		18	5V	5V	
19	LaserB	CMOS, 0/5V, max 14 mA	FPK	20			Connected to pin 21
21			Connected to pin 20	22	LaserA	CMOS, 0/5V, max 14 mA	PWM, frequency or Q-Switch
23	GND	GND		24			
25	5V	5V		26	Laser Gate[1]	CMOS, 0/5V, max 14 mA	

Note: E1701d can control various lasers, so pins are provided for each type.

Pin no. 10 will provide a 0-5V analog signal that needs to be scaled to 0-10V and connected to the Green wire of the laser. Pin no. 22 will be connected to the Black wire, but not directly. It has to be scaled to 24V, having a modulation rate of less than 20 kHz. Pin no. 2 will be a common ground for all the connections from laser to controller. Red, Red and white wires will be connected to 24V and ground of power supply respectively.

Component description:

a) IC 7812: To convert 24V power into 12V power
b) LM 741: To convert the 0-5V analog output to a 0-10V range suitable for the laser
c) 24V power supply
d) IRF540N: to convert 5V PWM signal to 24 V PWM signal up to the frequency of 20kHz
e) Capacitors to prevent the spike of voltage in the circuit

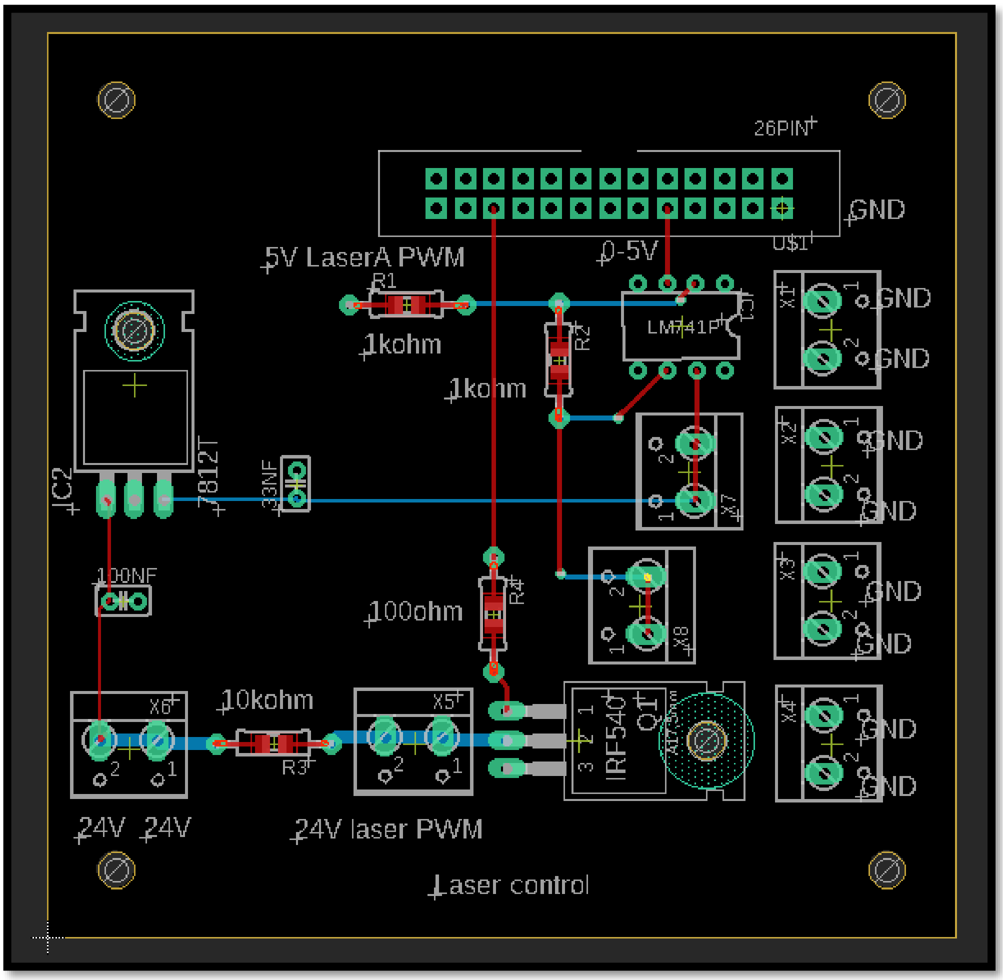


Figure 20: PCB design to give signals from controller to laser

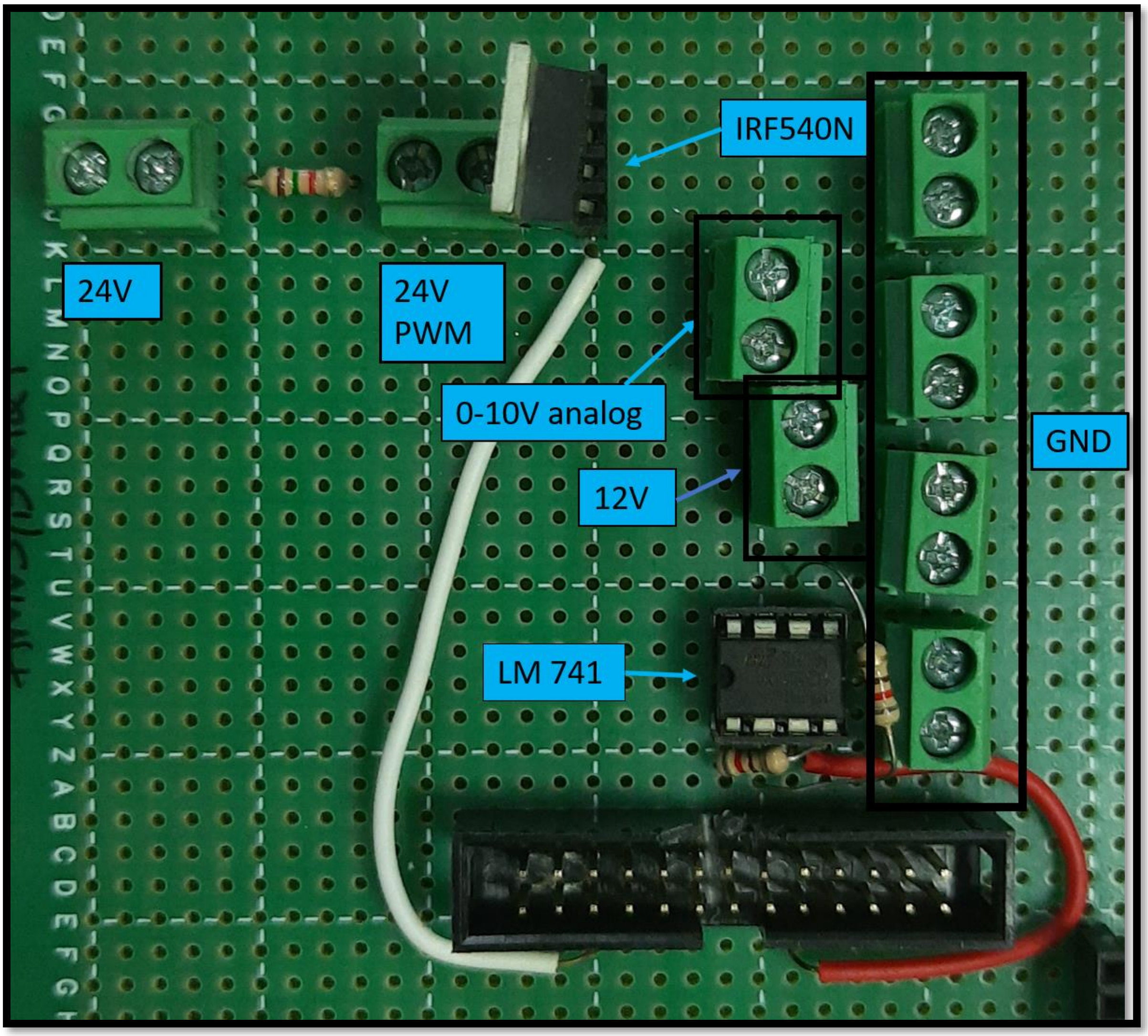


Figure 21: PCB for testing laser signals from the controller

The PCB was tested successfully using an oscilloscope. The 24V modulated pulses at the output are at 180-degree phase difference, but it will not create any problem for our system as the laser is required to be turned on at a suitable modulation rate.

3.3.2 Collimator lens

Collimator lens works as a connector between the head of the laser and the galvanometer scanner. It is used to produce a beam of parallel rays to avoid divergence.

Figure 22: Collimator lens

3.3.3 Galvanometer scanner

Considering the fusion is done on the x & y-axis, and the platform moves in the z-direction. So, there are two ways to move the beam to the desired point

i) Move the laser head or collimator using motors in both directions: It would produce many vibrations, producing errors in our system. As the laser should be highly focused, vibrations would make the beam spread and reduce the intensity of the beam. Also, the laser traveling to different locations would have different intensities.

ii) Use galvanometer optical scanners for steering the laser beam: This has a motorized mirror mounted to steer the beam as per the requirement. It would have no vibrations, and the collimator is not required to move every time so that a focused beam can be obtained without any error. Therefore, galvanometer scanners have two mirrors to steer in x & y-direction.

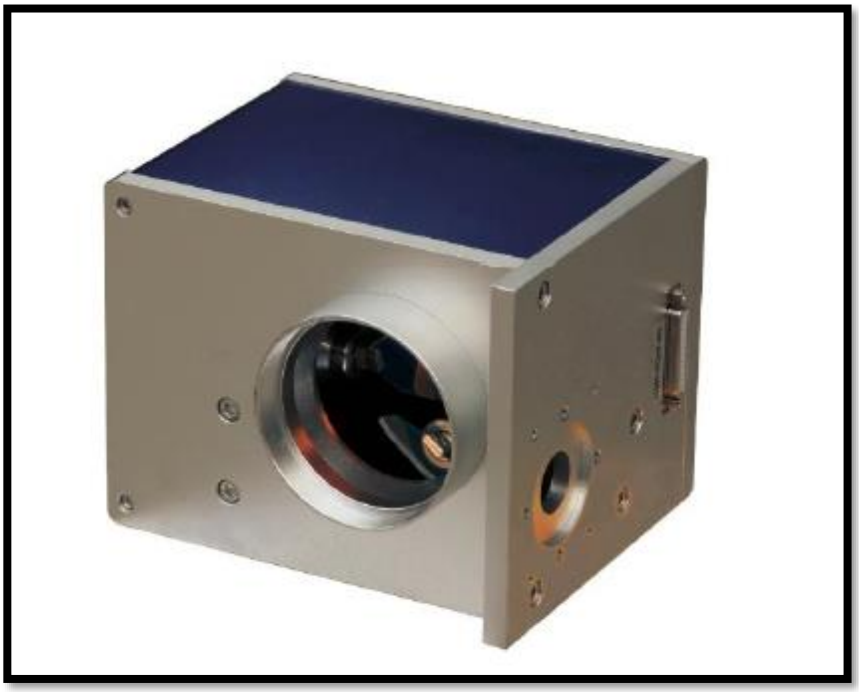


Figure 23: Galvanometer scanner

Table 3: Signals provided by E1701d for controlling scanner

Upper Row Of Pins	**Signal**	**Voltage**	**Remarks**	**Lower Row Of Pins**	**Signal**	**Voltage**	**Remarks**
1	CLK-		XY2-100- / XY2-100-E- compatible signals	**2**	CLK+		XY2-100- / XY2-100-E- compatible signals
3	SYNC-			**4**	SYNC+		
5	X-			**6**	X+		
7	Y-			**8**	Y+		
9	Z-			**10**	Z+		
11	LaserA	CMOS, 0/5V, max 14 mA	Laser control signals	**12**	GND	GND	Laser control signals
13	Laser Gate	CMOS, 0/5V, max 14 mA		**14**	GND	GND	
15	LaserB	CMOS, 0/5V, max 14 mA		**16**	ExtStart	CMOS, 0/5V	Input control signals
17	5V	5V		**18**	ExtStop	CMOS, 0/5V	
19			do not connect	**20**	GND	GND	XY2-100- / XY2-100-E- compatible signals
21	GND	GND	XY2-100- / XY2-100-E- compatible signals	**22**	GND	GND	
23			do not connect	24			do not connect
25			do not connect	26			do not connect

Galvo-scanners have a power cable of 24V, -24V, GND and grounding to earth as well, and for signaling, it has CLK+, SYNC+, CLK-, SYNC-, X+, Y+, X- and Y- cables which will be connected to pin 2,4,1,3, 6,8,5 and 7 respectively.

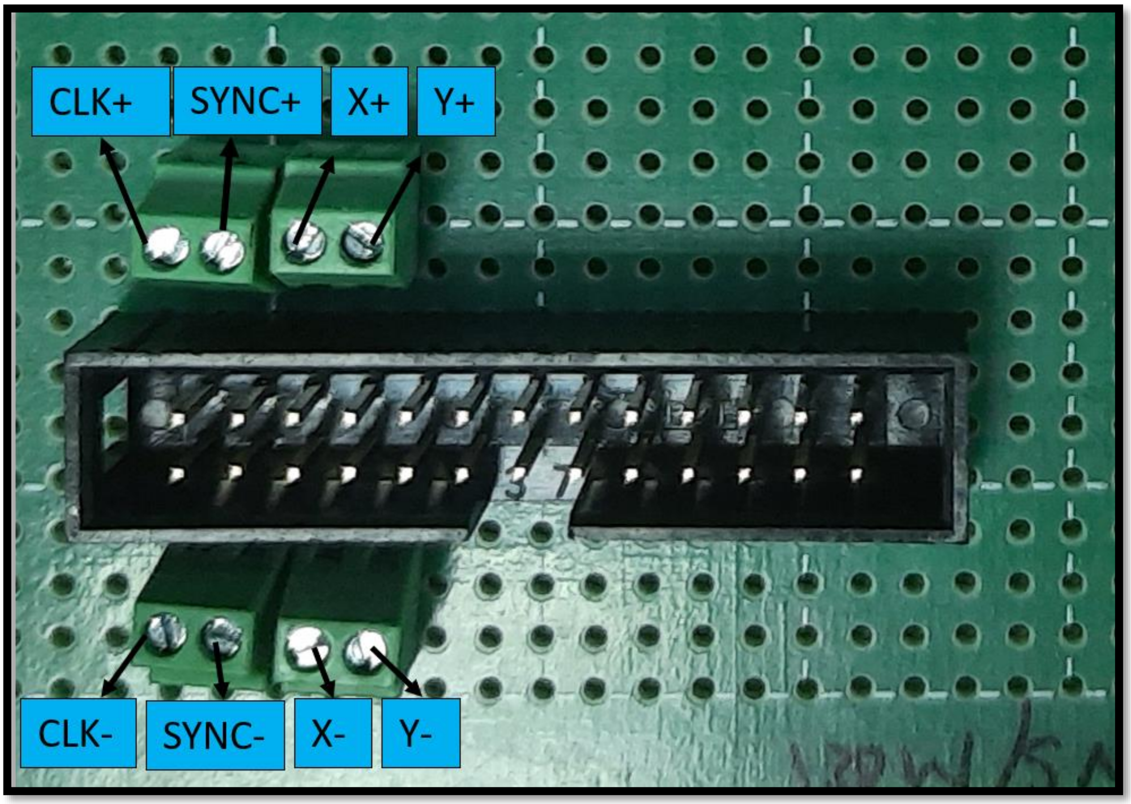


Figure 24: Connections for scanner to controller

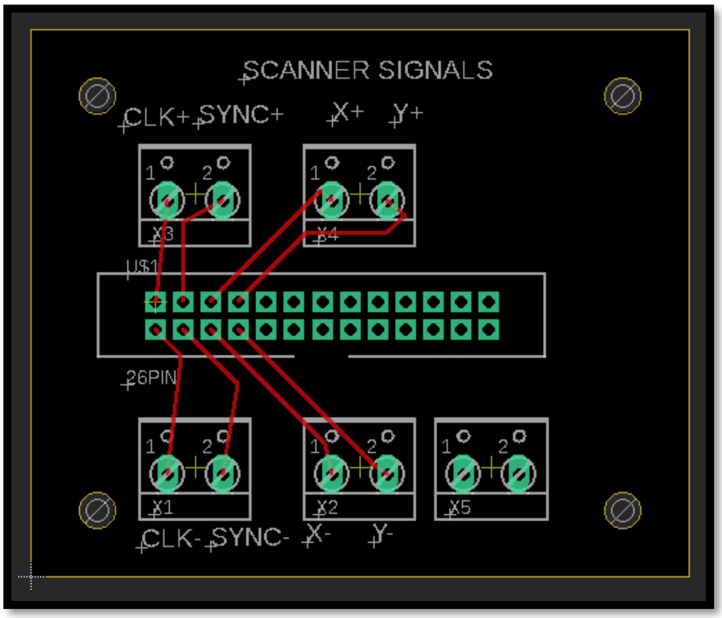


Figure 25: PCB design for connection of scanner to controller

During the scanner testing, it made some noise, and one of the mirrors broke down. The mirror is not available in the Indian market, and the supplier from China is asking to send back the galvanometer scanner to their lab to repair it.

3.3.4 F-theta lens

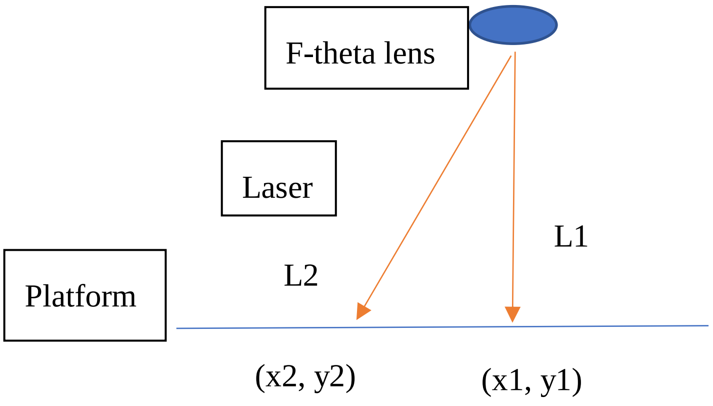


Figure 26: Laser striking on the platform

From Figure 26, if the laser has to fuse on points (x1, y1) and (x2, y2), then it has to travel distance L1, L2 where L1 < L2, which will reduce the intensity of the laser for (x2, y2) as compared to (x1, y1). This will lead to either fusion not taking place or inappropriate fusion for different coordinates. For the laser to weld those points, it should have the same intensity and similarly for all points on the plane. F-theta lenses are made so that beams have the same intensity all over the plane. The f-theta lens being used has a focal length of 650mm, a working distance of 697mm, and a maximum scan area of 400mm*400mm that matches our requirement.

Figure 27: F-theta lens

3.4 Vertical motion of the system

Steel powders have a diameter ranging from 38µm to 300µm[31]. So, the minimum possible layer can be 38µm thickness, meaning that the desired motion of the platform at each step should be less than or equal to 38µm. Considering this, the platform is accompanied by a system that can move it 25µm at each step.

Maximum mass of the steel powder: ρ*Volume → 7.8g/cm^3*40cm*40cm*40cm/1000 = 499.2kg

3.4.1 Platform

The platform needs to be designed such that deflection in the z-direction of the platform should be minimum. The maximum deflection would occur when a metal of maximum dimension is formed, i.e., when a cuboid of 400mm*400mm*400mm is manufactured. So, a cuboid of the above dimension is considered for simulation. The system is cantilevered as other sides will be used for the powder delivery mechanism.

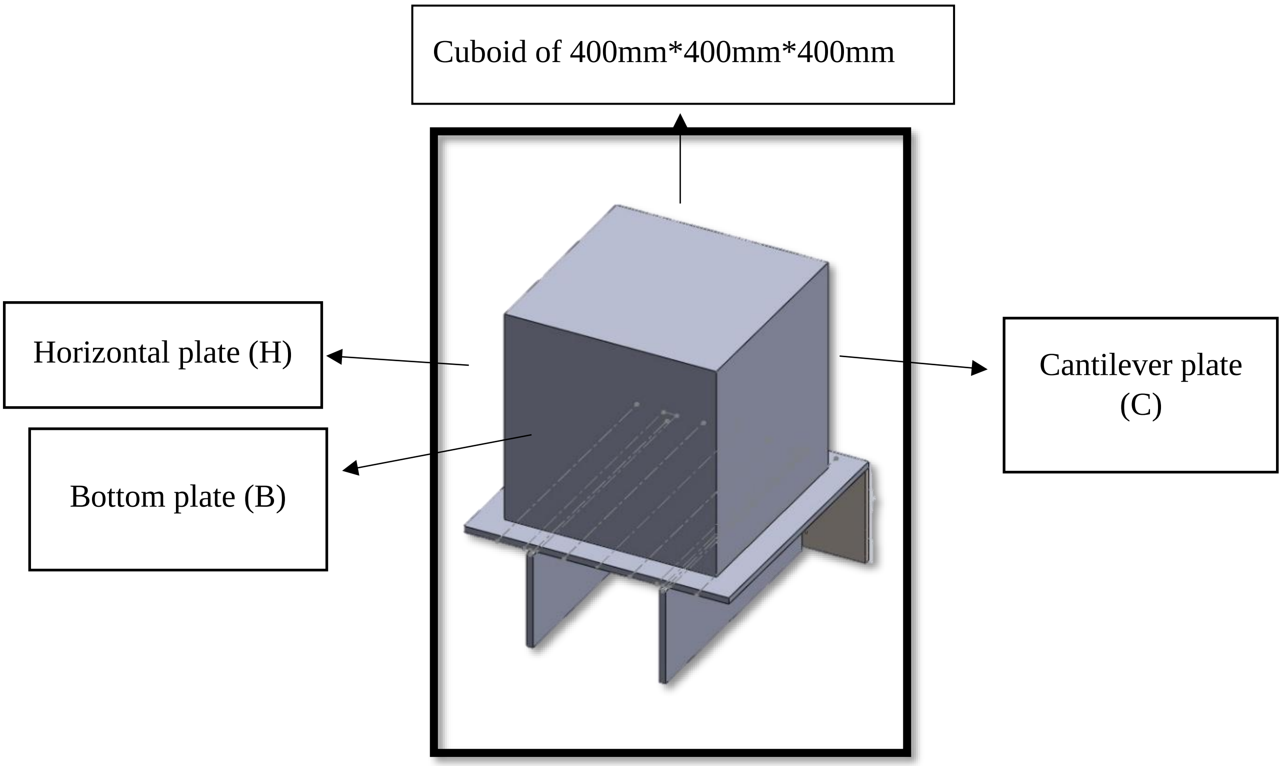


Figure 28: Design of platform with two bottom plates

Simulation of different designs of plates on the platform is done on SolidWorks, and the result is as follows:

Table 4: Platform simulation for different plate thicknesses for various combinations

H thickness (mm)	B thickness (mm)	No. of B (mm)	Distance b/w consecutive B (mm)	C thickness (mm)	C length (mm)	Depth of plate (mm)	Total volume (cm3)	Max. Disp. (um)
12	25	2	250	12	180	180	4,392.00	9.77
12	12	2	250	12	180	180	2,108.16	16
12	12	2	250	25	180	180	2,052.00	15
12	25	2	250	25	180	180	4,275.00	9.3
25	25	2	250	25	180	180	4,275.00	8.67
12	12	4	125	12	180	180	4,216.32	9.733
12	25	4	125	25	180	180	8,550.00	7.8
12	6	4	125	12	180	180	2,108.16	16.34
Cross plate								
12	12	1		12	180			32
Mesh plates								
25	12	1		25	180	180		14.68
12	12	1		12	180	180		16.82
I-beam								
25		2	250	12	120	120	1,428.58	39.45
12		2	250	12	180	180	2,814.09	16.32
12		4	250	12	180	180	5,628.18	9.27
12		2	250	12	180	180	6,281.29	10.97
Rectangular beam								
12	10	2	250	12	180	180	5,028.07	8.9

12	10	2	250	12	180	180	6,589.67	7.9
12	10	1		12	180	150	3,685.24	17
L-beam								
12	10	2	250	12	180	180	2,525.87	19.45

A horizontal plate of 500mm*500mm is used in which fusion would take place. Based on the simulation, cantilever thickness of 12mm, four bottom plates with 12mm thickness equally spaced at 125mm, and horizontal thickness of 12mm. Factors like deflection, volume, and cost are considered for selecting suitable parameters. As volume increases, weight increases, which increases cost due to material and also to support such heavy load, e.g., the motor of higher torque would be required in such case, which would be costlier. Maximum deflection is observed at the cuboid's top corner, which is away from the cantilever.

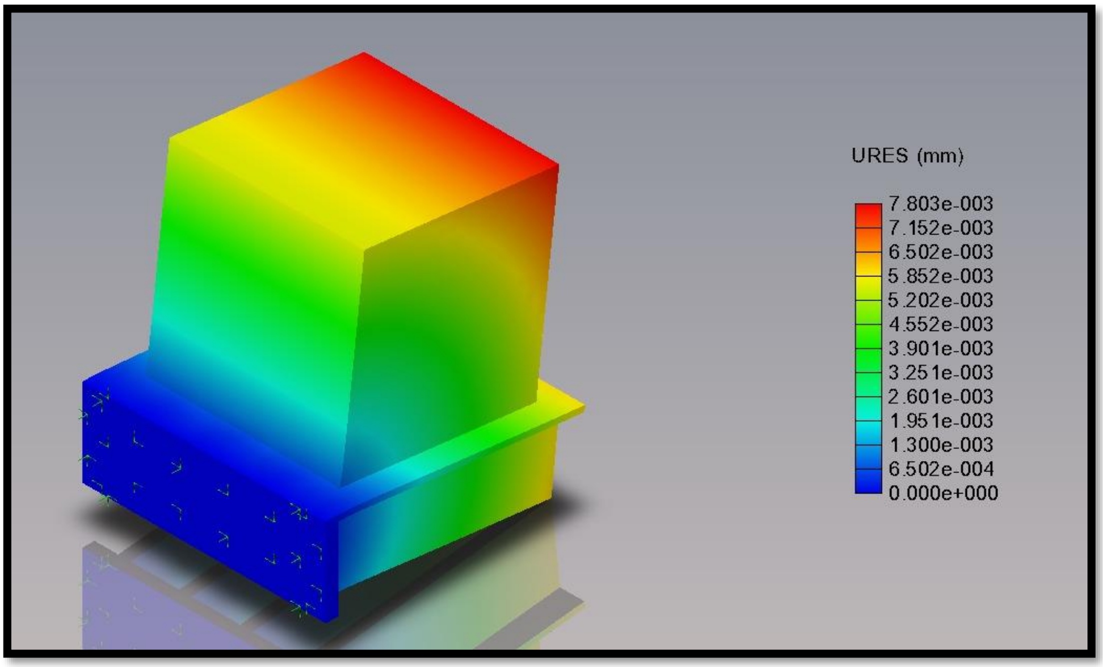


Figure 29: Deflection when four bottom plates and horizontal plate of 12mm, and the cantilever of 25mm are used

Figure 30: Platform after fabrication

3.4.2 Supporting system

a) Ball screw vs. Lead screw: Ball screws and lead screws are generally used for converting rotary motion into translation motion.

Table 5: Difference between the ball screw and the lead screw

Ball screw	Lead screw
High accuracy	Low accuracy
Low coefficient of friction	High coefficient of friction
Expensive	Cheap
Require braking system	Self-braking system
Have higher life	Have less life

The main requirement is accuracy, as we need a motion of 25µm each time, which is impossible in the lead screw. Ball screw of 32mm diameter with 500mm stroke length and 600mm total length is selected for our use. The minimum pitch available is 5mm, and the number of turns on the ball screw are 5.

For one rotation i.e. 360 degrees → Linear motion = 5(number of turns) *5(pitch) = 25mm

To get linear motion of 25µm → 0.025*360/25 = 0.36 degrees

So, to move 25 microns each time, we need to rotate the ball screw by an angle of 0.36 degrees.

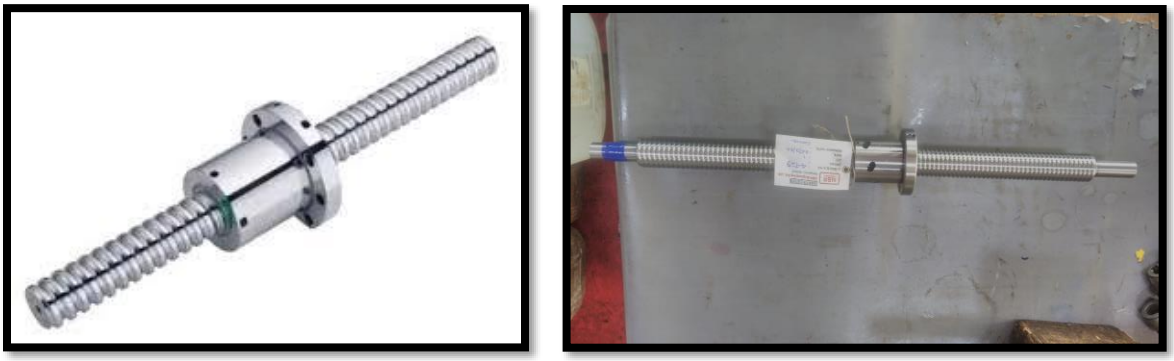


Figure 31: Ball screw along with nut

The ball screw has a nut on which the platform will be connected. A cuboidal plate is bolted with the platform and the flange nut to connect the flange nut to the platform. The system still has chances of torsion, so linear guides are used to prevent such moments.

The ball screw was purchased with a pitch of 5mm and three turns, which makes the lead equal to 15mm i.e. for one rotation, the platform will move 15mm. So, now our system will be more precise. At 0.36 degrees, the platform will just move 15 microns.

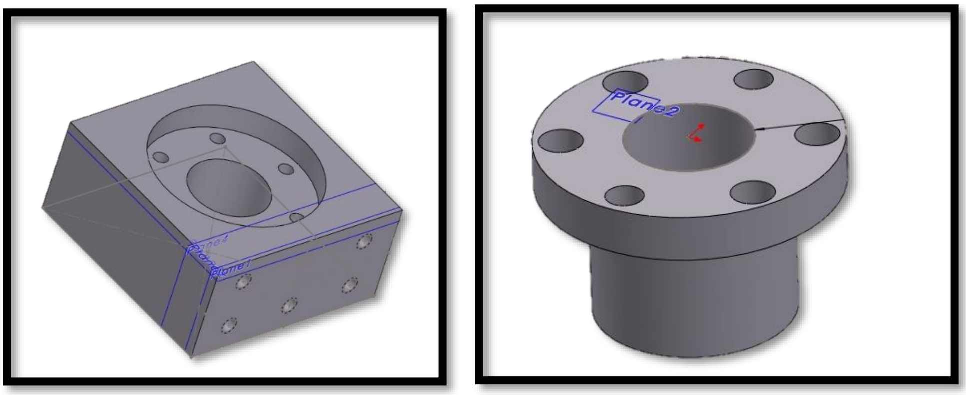


Figure 32: CAD model of Cuboidal plate (on left) and nut (on right)

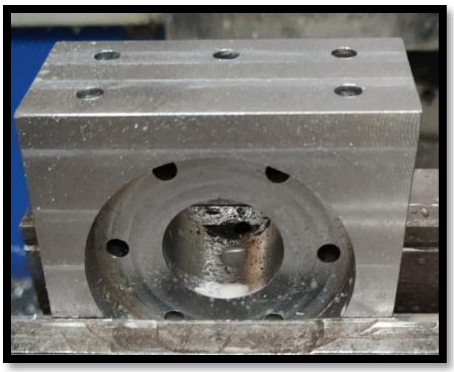
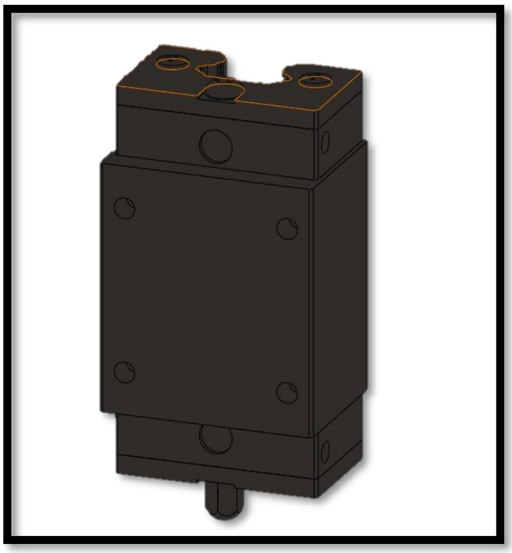


Figure 33: Cuboidal plate

a) Linear guideways: 4 linear guideways are used, and each of them has a dynamic load rating of 11.38kN. We have assumed our system to be 1200kg (maximum weight due to steel powder + weight due to platform), i.e., 12kN approx. It helps the platform to avoid any torsional effects.



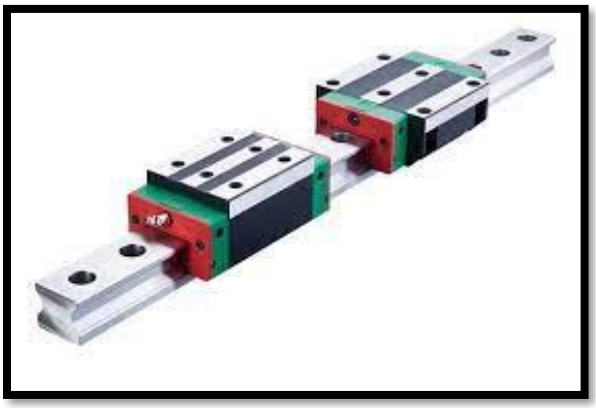


Figure 34: Linear guideways: CAD model (on left) & actual image along with linear rail (on right)

b) Linear rails: 2 rails are used; 2 guideways would be connected on each rail.

Figure 35: Linear rail

c) Motor: A servo or stepper motor can rotate the ball screw 0.36 degrees. But as controller E1701d can control only the stepper motor directly, any comparison between stepper and servo is not required. As per the calculation based on the weight, i.e., 12kN, the motor should provide torque up to 15Nm based on the ball screw we are using. For a stepper motor, when the RPM (rotation per minute) increases, the motor's torque decreases. A maximum limit of vertical motion speed is set to 5mm/s for the platform.

In 1 sec: 5mm linear motion

25mm linear motion requires 5sec, i.e., for one rotation, it would take 5 seconds

Therefore, it would do 60/5, i.e. 12 rotations in one minute. So, the motor should provide 15Nm torque at 12RPM.

A suitable motor has to be selected based on the above specifications.

d) Support plate and Bracket plate: To support the rails and avoid vibrations generated by the motor, a vertical plate and a bracket plate are installed to serve the purpose.

Figure 36: Support plate (on left) & bracket plate (at right)

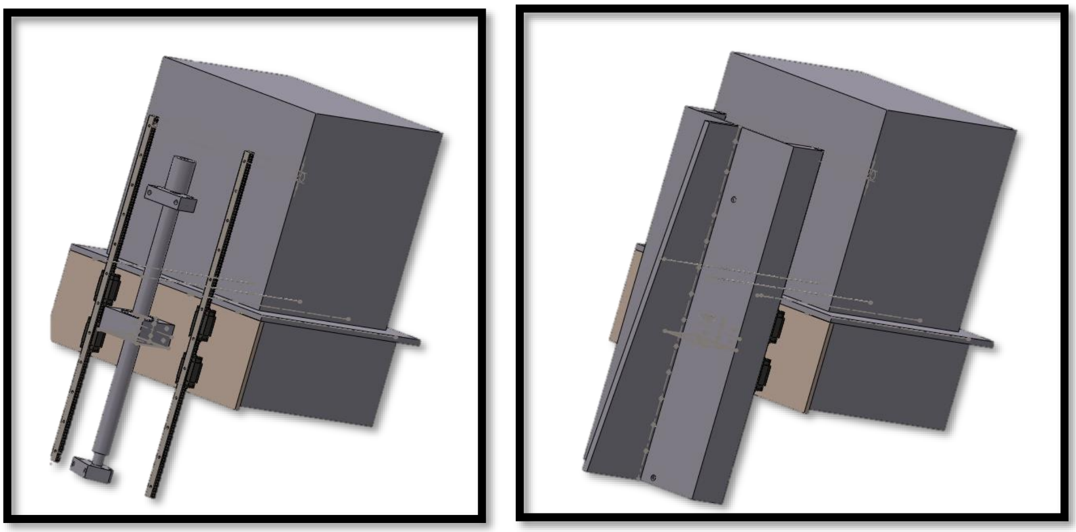


Figure 37: Complete assembly of vertical motion system without support plate (left) & with support plate (right)

Figure 38: Assembly of the vertical moving system

3.5 Powder spreading mechanism

Generally, metal powders are abrasive because of their rough surface and high strength. Considering layer thickness to be 25µm for which vertical system is designed. The layer would be spread over an area of 400mm*400mm every time.

Volume of steel powder spread every time: 400mm*400mm*0.025mm = 400mm^3 i.e. 4mL

Total volume of steel powder required: 400mm*400mm*400mm = 64*10^6 mm^3 i.e. 64 L

3.5.1 Feed hopper

So, a system with a capacity to hold 64L or more is required, and a powder delivery mechanism that delivers a minimum of 4mL of powder every time.

So, a feed hopper is designed with a rotary mechanism to perform the above function.

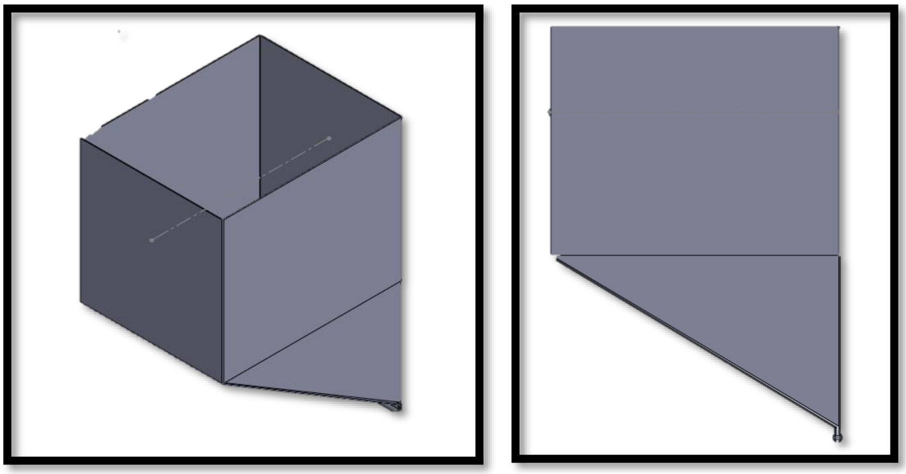


Figure 39: Feed hopper: Isometric view (left) & Front view (right)

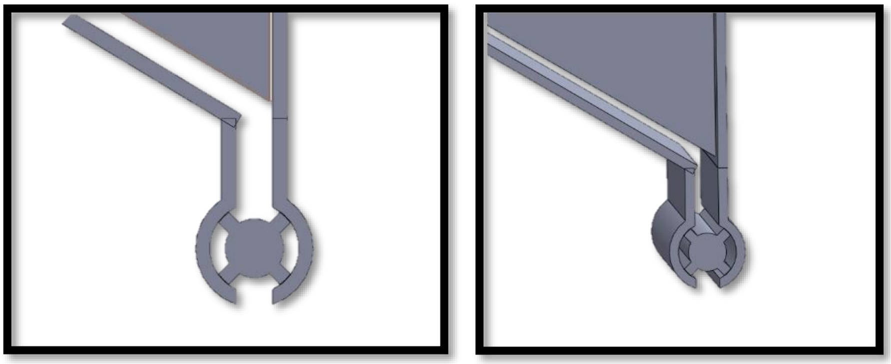


Figure 40: Powder delivery mechanism: Front view (left) & Isometric view (right)

Figure 41: Feed hopper

3.5.2 Roller and Spreader

After the powder has been poured into the platform, it needs to be spread over the platform. A spreader is designed to spread the powder, and a roller is designed to break the agglomerates. Due to the abrasive nature of the powder, N.K. Joy and M.A. Cullinan[25] coated spreader and roller with ceramic and PTFE6. Following (Figure 42, Figure 43) were the designs proposed by N.K. Joy and M.A. Cullinan for spreader and roller:

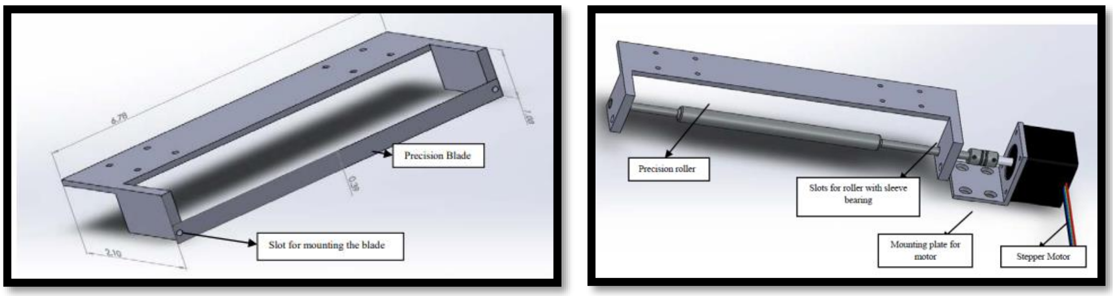


Figure 42: Design of spreader (left) & roller (right)[25]

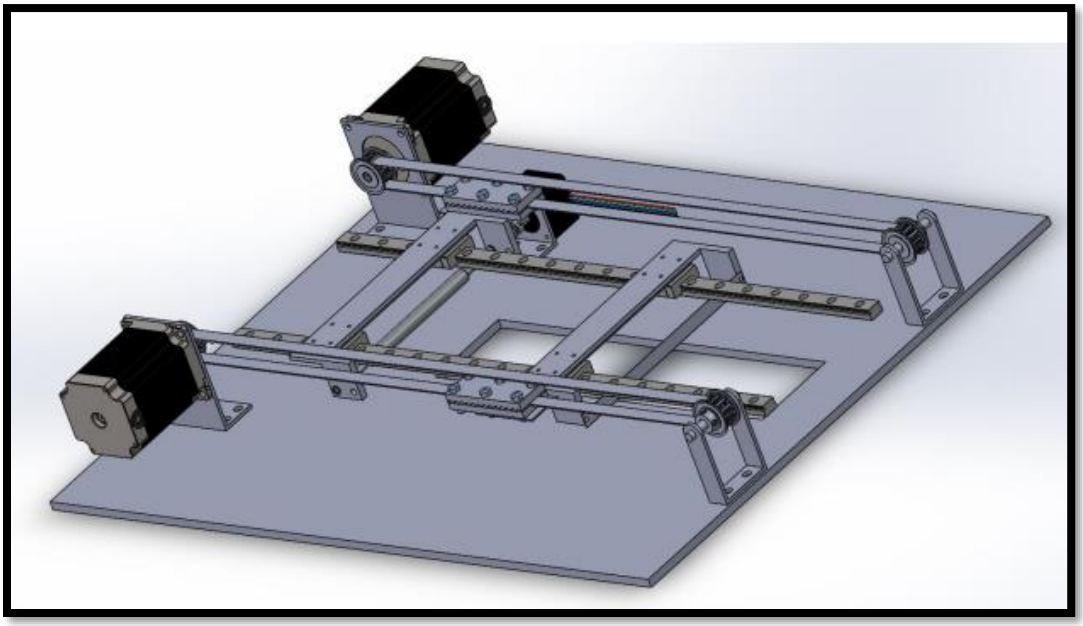


Figure 43: Completer assembly of spreader and roller[25]

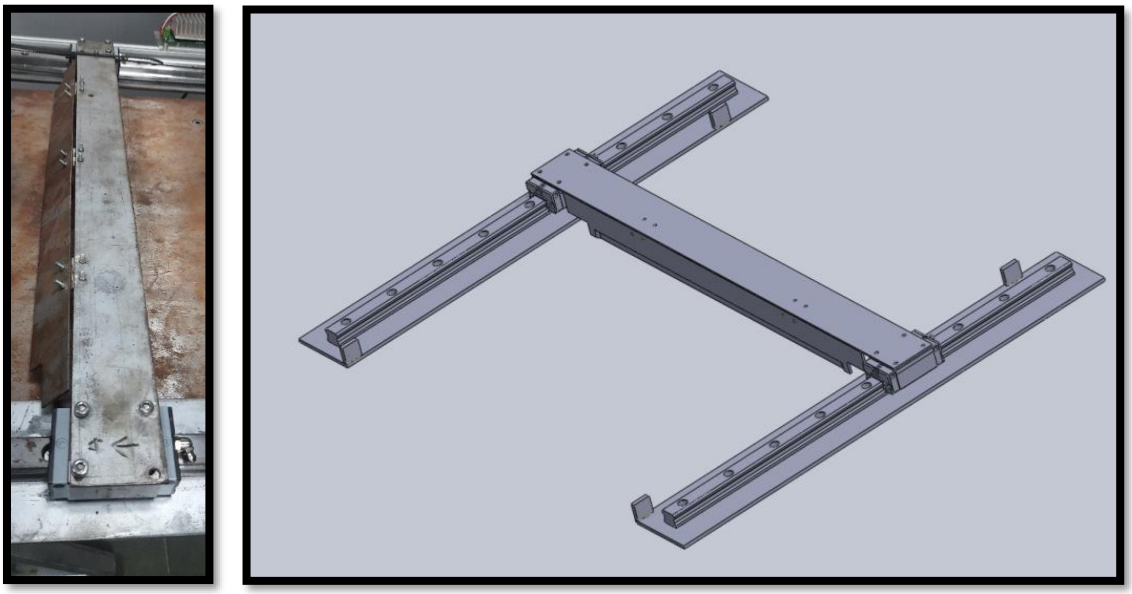


Figure 44: Spreader design

3.6 Feedback sensors

Feedback sensors can be integrated into the setup for various purposes, i.e., referencing stepper motors and sensors to verify that the platform is moving the distance as required.

Endstop limit switch can be used for reference purposes. It has a mechanical switch that is HIGH when not pressed and becomes low when pressed. When the motor returns to its home position and strikes the switch, it will signal the controller to stop the motor.

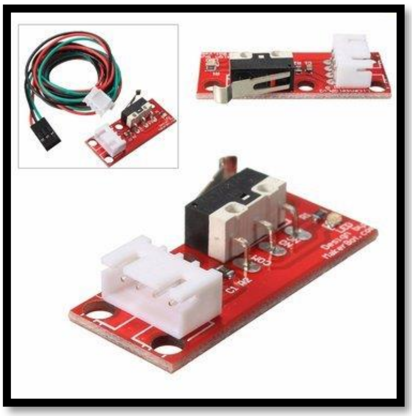


Figure 45: Endstop limit switch[32]

Laser-based proximity sensors can be used to verify motor displacement after each layer is sintered.

Chapter 4

Selection of steel powder and its parameters

Many steel powders are present in the market with different compositions and ways of production. 316L, H13, P20, and 18Ni200 are the widely used powders. H13, P20, and 18Ni300 mainly consist of martensite and a small amount of austenite due to the high cooling rate during the gas atomization process. Yan J. et al.[33] found that all possess a layered surface structure, consisting of a thin iron oxide layer at the outermost surface and a metal matrix at the inner surface. It is found that the presence of such an oxide layer can improve the absorptivity of steel powders.

316L stainless steel powder is highly used in medical applications. In the setup designed, an inert gas enclosure has not been provided yet, so the selection of steel powder should be such that it oxidizes less during the sintering process. As per American Society of Metals (ASM)[34], the maximum service temperatures at which steel powder resists oxidation in dry air are as follows:

Table 6: Maximum service temperature for various grades of steel

GRADE	INTERMITTENT (°C)	CONTINUOUS (°C)
304	870	925
309	980	1095
310	1035	1150
316	870	925
321	870	925
410	815	705
416	760	675
420	735	620
430	870	815
2111HTR	1150	1150

From Table 6, it can be seen that 304, 309, 310, 316, 321, and 2111HTR can be used for sintering. And as per the market availability of powder and applications in industries, 316L is the most suitable powder which can be used for the designed setup.

M. Dewidar[35] worked on finding the influence of processing parameters and sintering atmosphere and found out: i) The 316L stainless steel sintered at 1200, 1250, and 1300 degrees

Celsius in the different atmospheres has porosity values at the order of 39.25% and 11.87%.; ii) Young's modulus and peak stress decreases with increase in porosity; iii) The 316L stainless steel exhibit higher strength, wear-resistance, and hardness when sintered in nitrogen as compared to when sintered in argon or vacuum atmosphere; iv) An optimum temperature for mechanical properties such as density, hardness and wear resistance in nitrogen is found to be 1300 degree Celsius for hard tissue applications. Similarly, O'Neill W et al. [36] found that: i) If melting occurs, the process relies on surface tension-driven melt displacement that distributes the molten value and bonds nearest particles into a conglomerate near full density. This process is susceptible to unwanted thermal gradients, reducing wetting and balling phenomena and poor layer properties.; ii) The chromium oxide formed has a higher melt temperature than iron. The super-heated pockets of iron are trapped in bags of chromium oxide. Further heating of these bags leads to catastrophic failure because of the explosive release of molten iron, thus reducing its controllability. That's why oxidation needs to be prevented.; iii) The thermal gradient can be reduced by controlling powder bed temperature just short of melt temperature.

Table 7: Fractional density obtained for different powders by direct laser sintering process[28]

Material	Laser power (W)	Scan rate ($mm\,s^{-1}$)	Layer thickness (mm)	Line spacing (mm)	Fractional density (%)
Fe	215	75	0.1	0.1	73.8
	192	75	0.1	0.1	73.8
	215	75	0.1	0.3	72.0
	192	75	0.1	0.3	71.0
	180	75	0.1	0.3	69.7
	162	75	0.1	0.3	68.5
	144	75	0.1	0.3	68.0
	125	75	0.1	0.3	67.4
Fe–0.8C	215	75	0.1	0.3	76.5
	192	75	0.1	0.3	75.0
	180	75	0.1	0.3	74.5
	162	75	0.1	0.3	73.1
	144	75	0.1	0.3	71.8
	125	75	0.1	0.3	70.0
	100	75	0.1	0.3	66.9
	215	50	0.1	0.3	78.1
	215	100	0.1	0.3	72.2
	215	125	0.1	0.3	71.4
	215	150	0.1	0.3	67.8
	215	200	0.1	0.3	64.2
	215	250	0.1	0.3	60.5
Fe–4Cu	215	75	0.1	0.3	74.9
	180	75	0.1	0.3	73.8
	144	75	0.1	0.3	70.7
	100	75	0.1	0.3	56.6
Fe–0.8C–4Cu–0.4P	215	75	0.1	0.3	80.6
	180	75	0.1	0.3	78.0
	144	75	0.1	0.3	75.0
	100	75	0.1	0.3	67.7
	166	300	0.1	0.3	59.0
	166	400	0.1	0.3	54.1
	166	500	0.1	0.3	51.3
	166	600	0.1	0.3	49.4
316L	215	50	0.05	0.3	93.6
	215	100	0.05	0.3	86.9
M2	200	50	0.1	0.3	88.2
	200	75	0.1	0.3	85.8
	200	100	0.1	0.3	84.5
	200	125	0.1	0.3	79.2
	200	150	0.1	0.3	76.6
	200	175	0.1	0.3	62.1

From Table 7, it can be inferred that 316L gives a higher fractional density of 93.6% compared to other powders and sintering best at 215W laser power, 50 mms^{-1} scan rate, 50 microns layer thickness, and 0.3mm line spacing.

Chapter 5

System assembly

5.1 Parameters selected for different parts

5.1.1 Platform

As discussed earlier, the platform should be such that the product can have a maximum dimension of 400mm*400mm. So, to have extra spreader space and drop powder from hopper to platform, the platform was fabricated with a length and breadth of 500mm*500mm. Based on the simulation results in Table 4: the thickness of the horizontal plate and cantilever plate is 12mm, the height of the cantilever plate and bottom plates are 180mm, and the thickness of the four bottom plates are 12mm, each 125mm away to distribute the load evenly. The length of the cantilever plate will be the same as the length of the platform, i.e., 500mm, but the length of the bottom plate will be 12mm less than that of the platform as the 12mm extra gets added up because of the thickness of cantilever plate.

Table 8: Dimensions of platform

Length of horizontal plate	500mm
Breadth of horizontal plate	500mm
Thickness of horizontal plate	12mm
Thickness of cantilever plate	12mm
Length of cantilever plate	500mm
Height of cantilever plate	180mm
Number of bottom plates	4
Distance between bottom plates	125mm
Thickness of bottom plates	12mm
Length of bottom plate	500-12 = 488mm
Height of bottom plates	180mm

5.1.2 Supporting system

To get high accuracy, i.e., in microns (25 microns approx.), a highly precise ball screw is selected with a diameter of 32mm to take the platform load and the product manufactured over it. The dynamic load capacity for the ball screw is 2301kgf which provides a safety factor greater than 3 (approx.) to the system. The height of the cuboidal plate is nearly 50mm, and the maximum vertical motion the platform should be able to do should be 400mm. So, a stroke length of 500mm was decided, and the remaining space (600mm - 500mm = 100mm) was given to fix the ball screw with the end supports (BK20, BF20) and for the coupler to connect it with the motor. Linear guideways and linear rails were used to prevent torsion of the system in any of the directions. Based on numerical calculations, the maximum torque requirement is

15Nm at 12RPM. So, a stepper motor with 30Nm holding torque is procured, keeping the safety of the factor in mind. Due to the ball screw and coupler, the height of the support system went up to 700mm, and an additional bracket plate was provided at the end to prevent torsion. A cavity was also kept such that the bracket plate fits into the supporting plate to avoid any slipping or misalignment and restrict the degree of freedom of the system.

Note: Till DDP I, procurement of ball screw with 5 number of turns was in process, but later, for more precision, procurement of ball screw with 3 number of turns was done. So, now for 0.36 degrees of motion, the system should move 15 microns instead of 25 microns. All other calculations are kept the same as the precision for the platform is increased, but layer thickness will be kept at 25 microns.

Table 9: Parameters for supporting systems

Ball screw diameter	32mm
Accuracy grade	C3
Pitch	5mm
Number of turns	3
Lead	5*3 = 15mm
Stroke length of ball screw	500mm
Total length of ball screw	600mm
Dynamic load capacity	2301 kgf
Number of linear guideways	4
Number of linear rails	2
Length of rails	700mm
Number of guideways per rail	2
Motor torque	15Nm at 12 RPM
Step angle required	0.36 degree
Minimum vertical motion possible	15 microns
Support plate length	700mm
Thickness of support plate	12mm
Bracket plate length	700mm
Bracket plate thickness	12mm

5.1.3 Feed hopper

The feed hopper was designed to hold the powder to manufacture the product of maximum dimension (400mm*400mm*400mm) at once. From Figure 39 (right) and Figure 41 (left), it can be seen that one side is kept flat. The reason for that is to avoid hopper interference between the path of the laser; otherwise, the platform length would have increased. For 25 microns layer thickness, the hopper should deliver 4mL of powder every time.

Table 10: Parameters for feed hopper design

Capacity of feed hopper required	64L
Volume of powder to be delivered each time	4mL

5.1.4 Roller and Spreader

The spreader's length depends upon the powder's length to be spread, so it can be inferred that it has to be greater than or equal to 400mm. Two linear rails of 520mm and two linear guideways were also procured for the motion of the spreader.

Table 11: Parameters for spreader

Length of spreader	400mm
Length of linear rail	520mm

5.2 Controller

Laser signals were generated and verified on the oscilloscope. Apart from this stepper motor was tested with the controller. The commands were given to the controller via BeamConstruct.

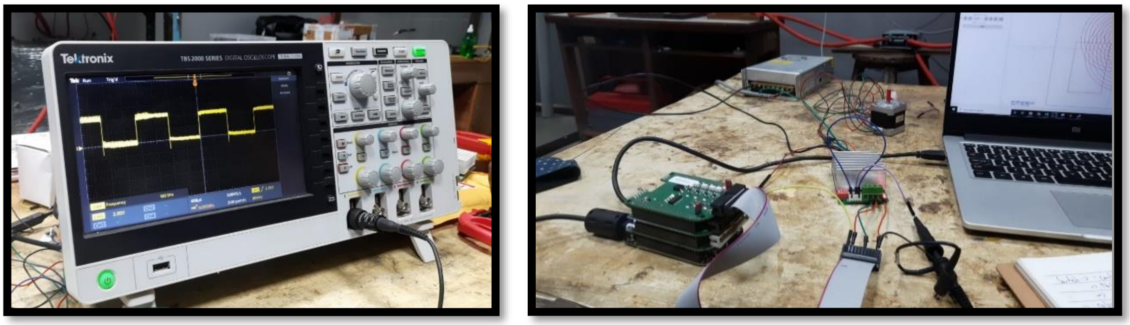


Figure 46: Readings measured on the oscilloscope of laser signals (on left) and motor simulation (on right)

Testing is done for:

a) Stepper motor driving vertical platform
b) Stepper motor used for hopper
c) Stepper motor used in spreader
d) Laser signals using the oscilloscope
e) Testing of endstop limit switch for referencing

5.3 Fabrication and Assembly

During the project following parts and their supporting parts have been fabricated or procured and then assembled:

a) Hopper
b) Vertical moving system
c) Support for the vertical moving system

d) Spreader

5.4 Selection of powder for sintering

Based on the current circumstances listed in Chapter 4, 316L stainless steel powder has been procured with the following composition.

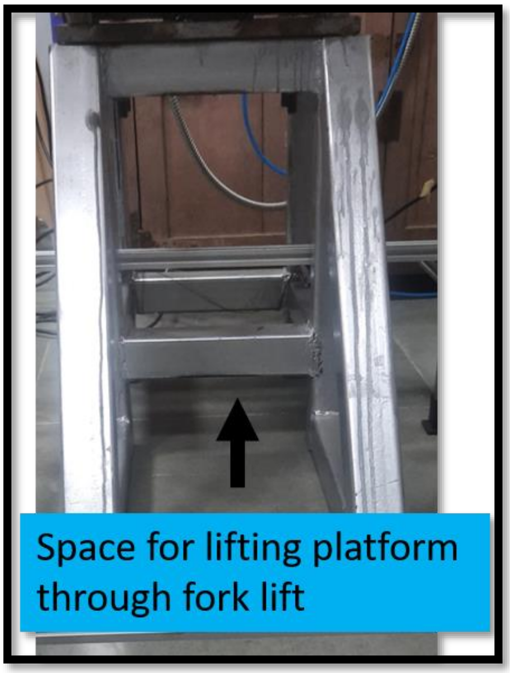
Table 12: 316L stainless steel powder composition (Source: Chemical Analysis Report from supplier)

Element	Percentage (%)
Manganese	2
Silicon	0.75
Phosphorous	0.05
Sulphur	0.03
Chromium	16.5
Molybdenum	2
Nickel	10.5
Carbon	0.03
Iron	Remaining
Melting point	1390 degree Celsius

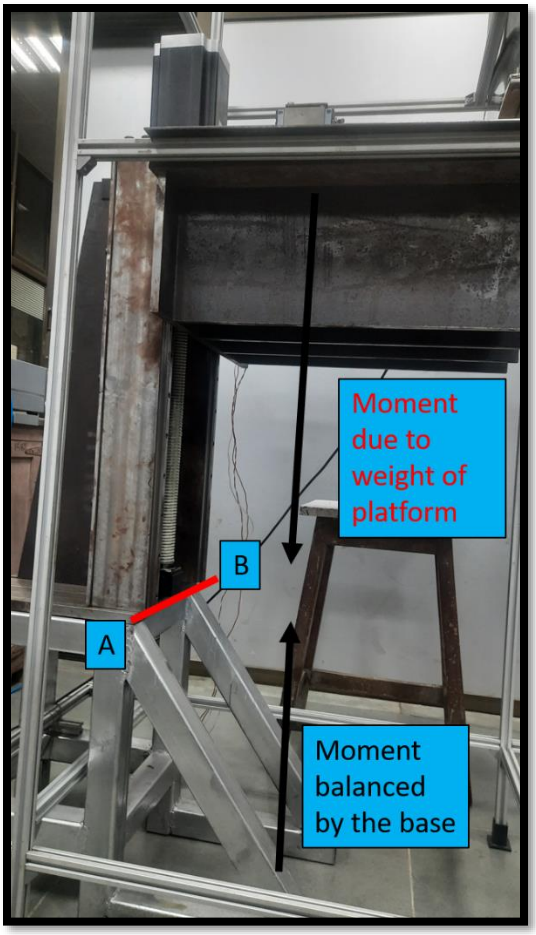
5.5 Base for the vertical support system

The base was designed to prevent the vertical moving system from toppling, so hollow square beams of 50mm wide and 2.5mm thick were used. There was another constraint that the square beam has a standard length of 6 meters, so the design was optimized such that toppling is prevented and sufficient height is provided to the system such that it becomes easier for the user to operate the setup. Space is provided at one side of the base so that forklift can be inserted to lift the system directly for shifting purposes.

(a)



(b)



(c)

Figure 47: Base to support the vertical moving system (a), (b) and (c)

5.6 Complete assembly

After procuring and fabricating all parts, the complete assembly can be seen in Figure 28.T-slot aluminium extrusions of 2020 are used to support the parts. On the top, the galvanometer scanner is attached to the collimator, which is attached to the laser fiber head. Then at the top right, the hopper is there with the flat surface in the direction of the platform. Then the platform is just below the hopper with its supporting system at the left. The spreader is between the vertical support system and the hopper and above the platform.

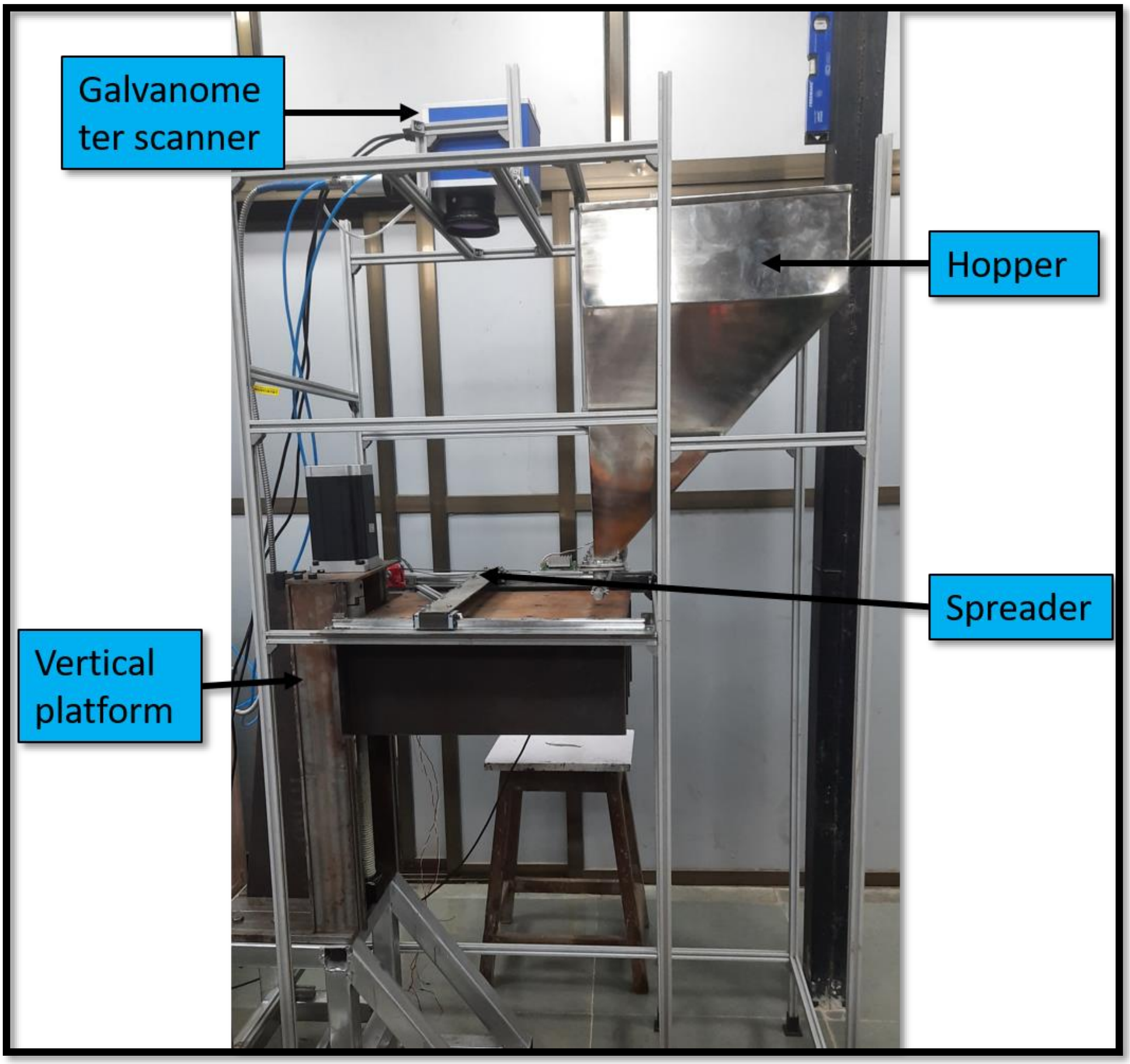


Figure 48: Complete assembly

Chapter 6

Conclusions

The project was entirely focused on developing a laser-based powder bed additive manufacturing machine. Components like laser, chiller, galvanometer scanner, controller (E1701d), collimator, linear rails and linear guideways for the spreader, and t-slot aluminium extrusions were already procured before the starting of the project. The main focus was to design and fabricate other essential components, i.e., vertical moving system, hopper, roller, and spreader. DDP I was mostly focused on designing all those parts and getting them fabricated or procuring directly from the vendors. Design for vertical moving system and hopper was sent for fabrication to the vendor. Based on the technical needs mentioned in Chapter 3 and Chapter 5, ball screw, end supports (BK20, BF20), linear rails, linear guideways, stepper motor, and its driver for moving the platform in a vertical direction were procured. Apart from that, laser testing directly from the PC was done. A basic understanding of the chiller, scanner, collimator, and the f-theta lens was done so that parts related to them can be procured or fabricated, e.g., the power supply for the scanner and laser. DDP stage II was mostly focused on getting the vertical moving system fabricated as it involved assembling many parts with lots of nuts and bolts. Apart from that hopper also got fabricated, so the stepper motor and its driver (taken from the lab inventory) were connected to the hopper and successfully tested them using controller E1701d. A coupler was also designed to do coupling between the motor shaft and the hopper rod. The spreader was also designed, and many prototypes were built using a 3d-printer. Then a final prototype was built from mild steel plates. Similarly, the stepper motor and its driver were procured for the spreader. The GT2 timing belt and timing pulley were also procured to move the spreader.

This project also involved designing PCBs for controlling platforms, laser, scanner, hopper, and spreader. The laser requires modulation input at 24V, and the frequency should be between 5kHz to 20kHz and 0-10V analog signal, whereas the controller can give 5V PWM only and analog signal between 0-5V only. So, a logic level shifter was made using a MOSFET (IRF540N) to scale 5V PWM into a 24V PWM signal, and an LM741 opamp was used to amplify 0-5V analog signal into a 0-10V signal by keeping a gain of two. EMI interference is also a big problem in the setup as three stepper motors are there in which the motor moving the vertical platform requires 90V, scanner uses four signals at the frequency of 2.2 MHz, modulation input for laser lies between 5kHz to 20kHz at 24V. So, a separate power source was used to cater to this problem. Proper EMI insulation needs to be done to avoid any interference. The power source for the stepper motor used for vertical motion contains an SMPS of 12V and 50A rating. A buck-boost converter is connected to the SMPS to adjust the voltage. It has a maximum capacity of 90V, which is sufficient for the motor. Endstop limit switch sensor was tested, which can be used for referencing stepper motors.

316L stainless steel powder was procured for testing as the service temperature for it without getting oxidised is quite high (870°C), and its applications in industries are enormous. Study-related to parameter selection for sintering was done to understand how different parameters influence the sintering process.

The project was quite inter-disciplinary as it involved designing components, lots of electronics, dealing with vendors, and planning things so that work is not stopped. The most challenging part was fabricating different components so that they work together while assembling. The dimension for one component sometimes becomes a constraint for the other. Designing in CAD software is easy but getting them fabricated and assembling them is tougher, especially if it involves higher precision.

Chapter 7

Future Work

The work done till now has been mentioned in the above chapters. Some of the work was left due to time constraints. There was a lot of learning from this project. Hoping the project will be continued, and the setup will be fully functional one day. Below are some of the short-term and long-term goals that can be worked upon.

7.1 Setup-related work

The fabrication part of the machine is almost completed. But due to the breakdown of the mirror, the galvanometer scanner cannot be used and is currently a big problem that needs to be sorted out immediately. A new galvanometer must be purchased or this one must be repaired by sending it back to the supplier.

Apart from that, complete testing of the machine has to be done altogether. Till now, components have been tested individually. Also, sensors (endstop limit switch) for referencing positions must be mounted. Proximity sensors will be used to check if the platform can move 25 microns every time. Enclosure needs to be designed so that the inert gas can be used. For spreading the powder, a spreader has been designed. But if agglomerates are there, a roller also needs to be designed.

7.2 Final aim of the project

After the machine is fully set, the sintering process and research work can be started on the machine. Process parameters can be worked upon to improve the quality of the product obtained. Different powders can be tried in the machine, and their microstructural analysis can be done. Additive manufacturing machines are relatively high in demand in industries but become unaffordable due to their high price. In such a case, this machine will be a suitable option. The ultimate aim of this project will be to commercialize it and make a boom in the market. It will allow researchers and industrialists to make complex parts and faster product prototyping.

Other essential components

1. Coupler: To connect motor of vertical system to ball screw

Figure 49: Coupler

2. Stepper motor driver for vertical motion

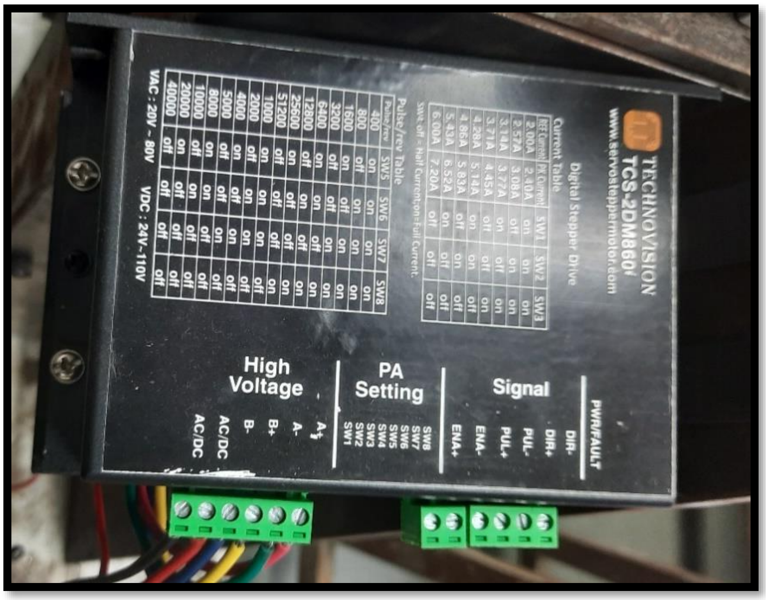


Figure 50: Stepper motor driver

3. Stepper motor for vertical motion of platform

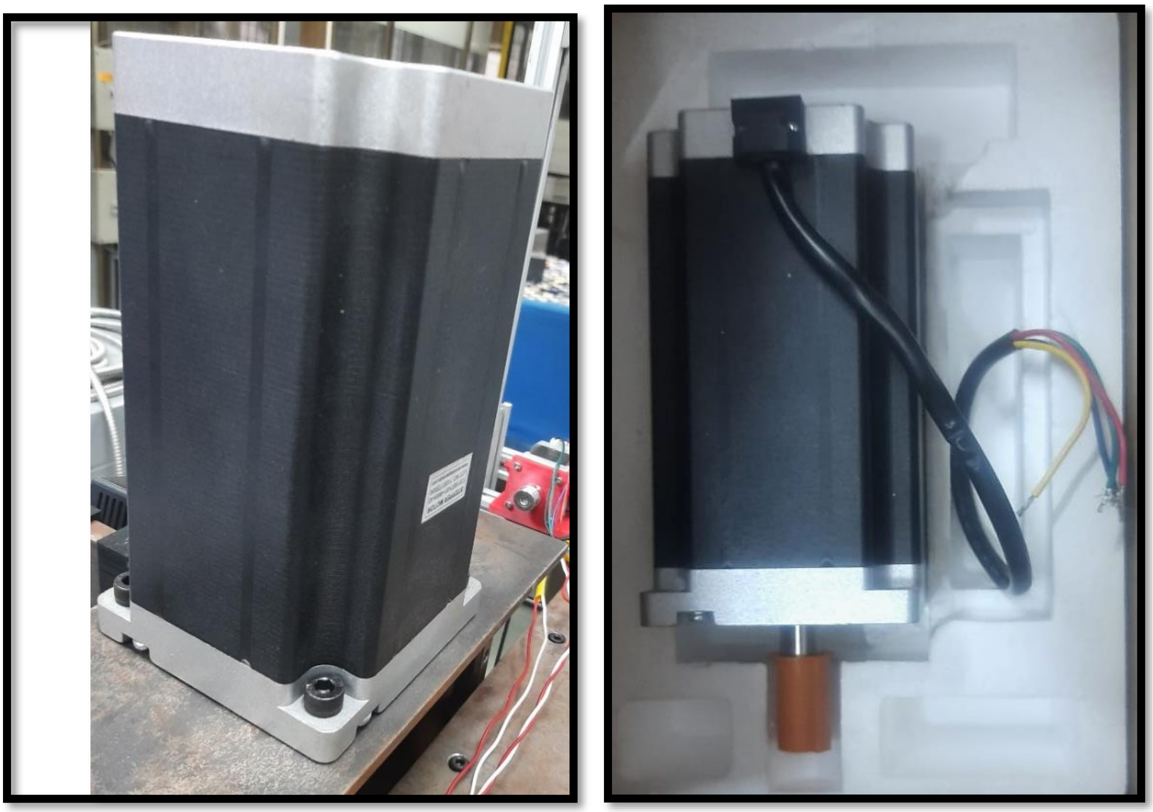


Figure 51: Stepper motor for vertical motion

4. Stepper motor for hopper along with coupler

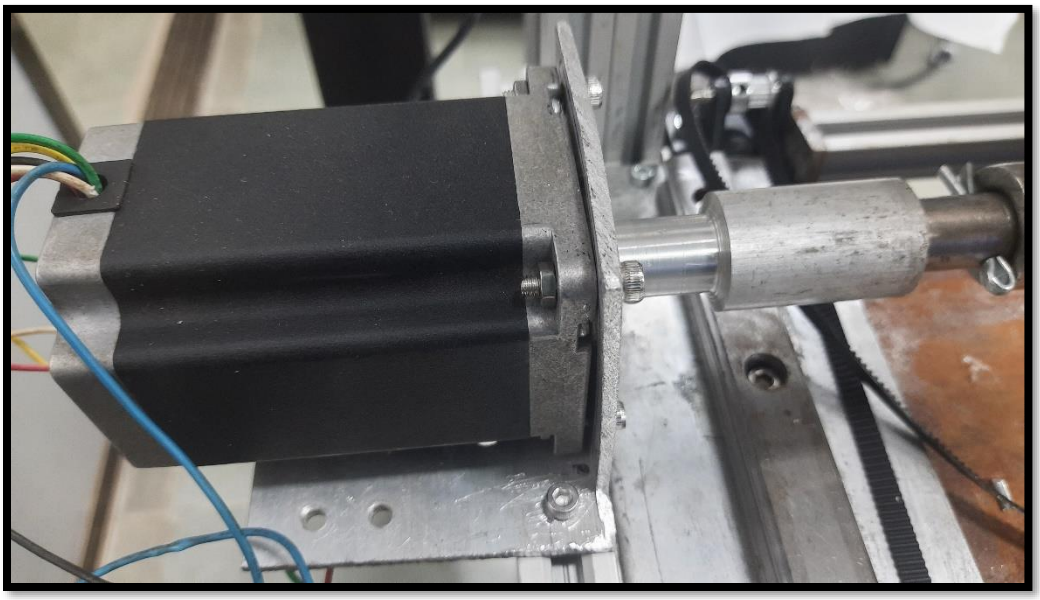


Figure 52: Stepper motor for hopper

5. Stepper motor driver for hopper

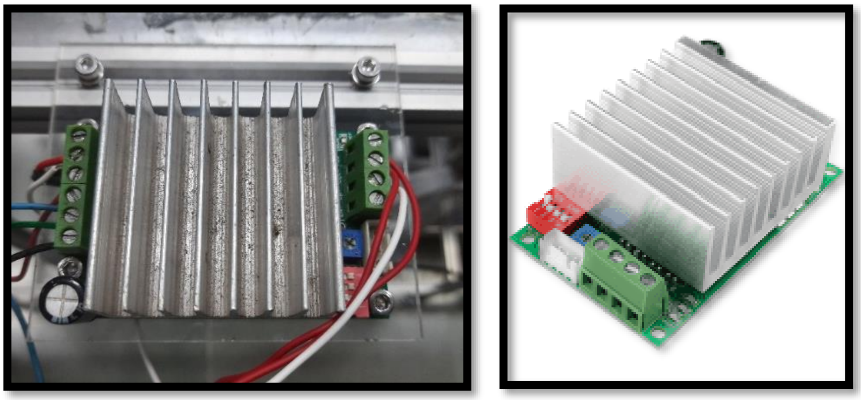


Figure 53: Stepper motor driver for hopper

6. Stepper motor for spreader

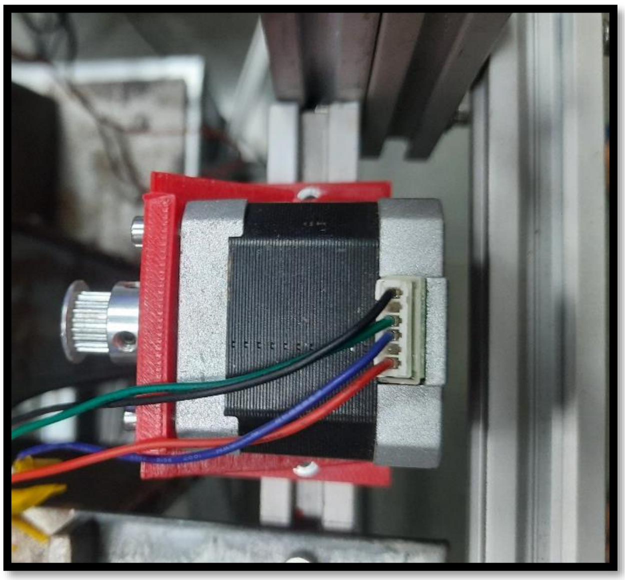


Figure 54: Stepper motor for spreader

7. Stepper motor driver for spreader

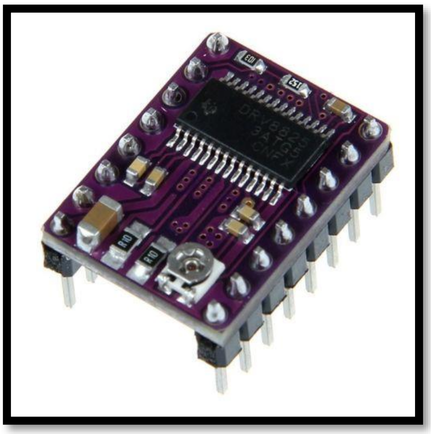
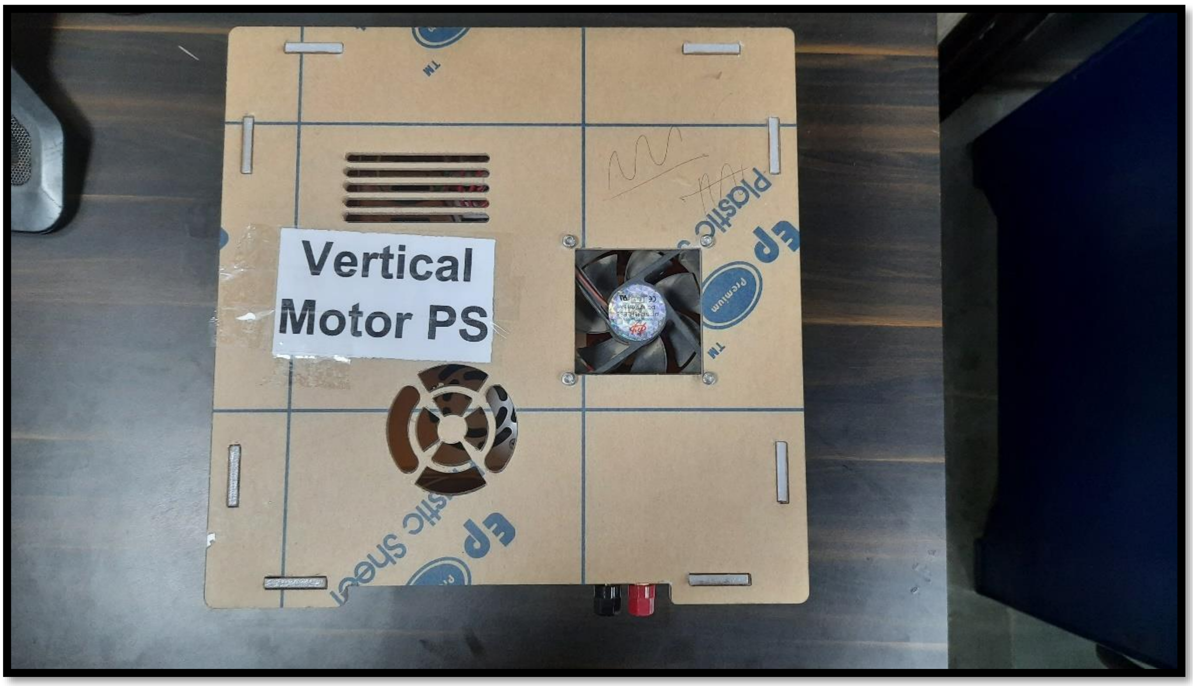


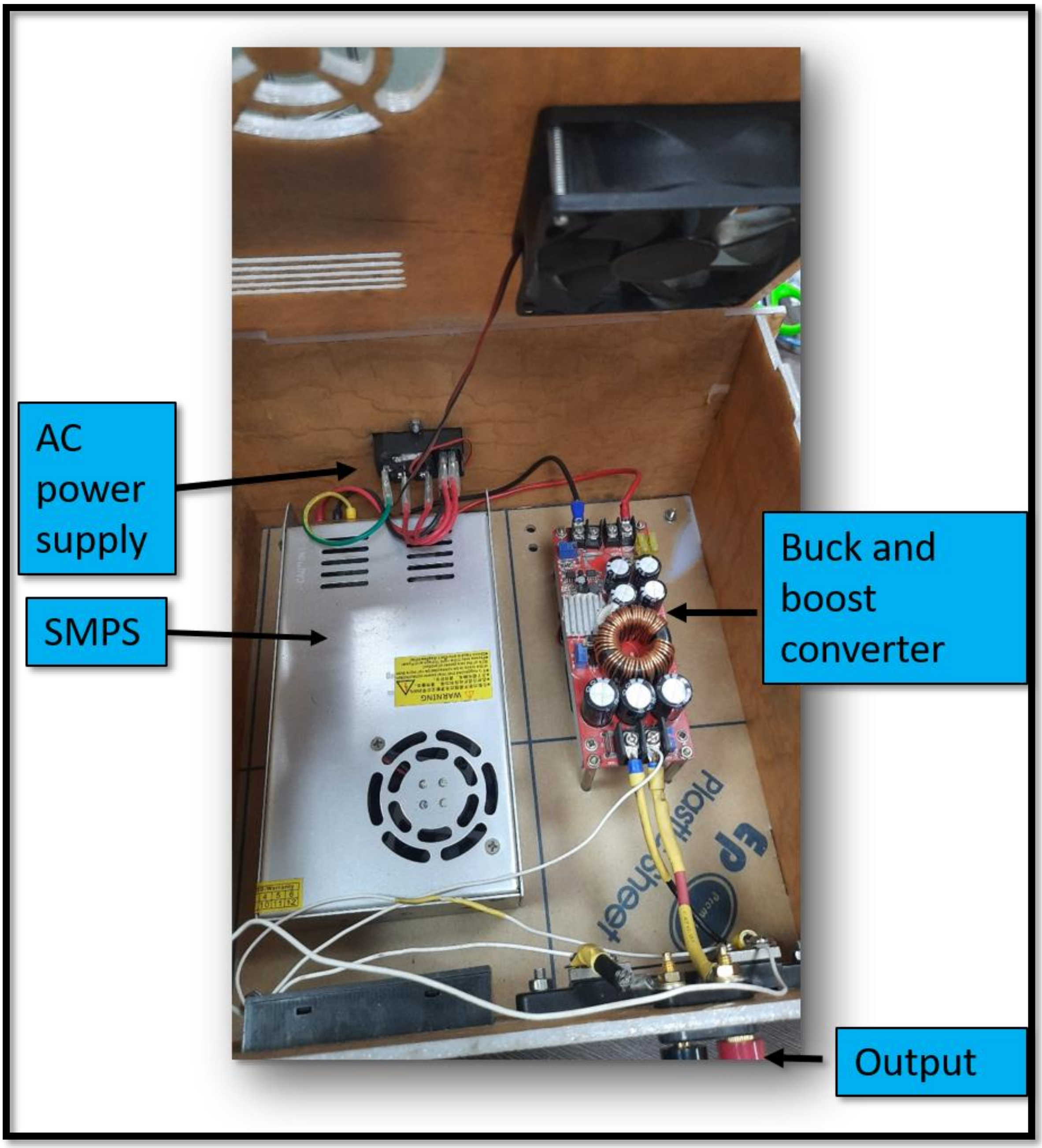
Figure 55: Stepper motor driver for spreader

8. Power supply for stepper motor providing vertical motion

(a)



(b)



(c)

Figure 56: Power supply for stepper motor providing vertical motion (a) Front view, (b) Top view, (c) Inside view

9. 24VDC 15A SMPS for laser

Figure 57: 24VDC 15A SMPS for laser

10. ± 24VDC 4A SMPS for galvanometer scanner

Figure 58: ± 24VDC 4A SMPS for galvanometer scanner

11. 24VDC 5A SMPS for stepper motor driving hopper

Figure 59: 24VDC 5A SMPS for stepper motor driving hopper

12. Base for vertical moving system

Figure 60: Base for vertical moving system

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project Rapid prototyping View project Investigation of Dimensional Accuracy/Mechanical Proper-ties of Part Produced by Selective Laser Sintering. *International Journal of Applied Science and Engineering* vol. 10 https://www.researchgate.net/publication/263238355 (2012).

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