Design, Development & Manufacturing of Multi Powder Hopper for Laser Cladding of Functionally Graded Materials

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We hereby recommend that the dissertation prepared under our supervision by

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Copyright Statement

Dedicated to my beloved Parents and all well-wishers who remained faithful and trust-worthy during this time

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Abstract

Laser Cladding is the subsidiary of Laser Material Processing which comprises of deposition of melted material upon the substrate with the aid of a laser beam. Laser Cladding is the combination of various disciplines such as Robotics, CAD/CAM, Instrumentation, Sensors and Powder Metallurgy.

Laser Cladding is performed through the deposition of powder onto the substrate. The powder is transferred through Powder injection, Wire Feeding and the Pre-Placed Powder methods. However, the Powder Injection Method is most efficient and effective among all due to its accuracy and controllability.

Functionally Graded Materials are the materials having variable composition, porosity and microstructure across the volume and deposited length. FGMs are responsible for the development of variable graded components for complex operating conditions. Moreover, the contributions of FGMs in structure repair areas are well appreciated.

This research aims to develop the novel multi powder injection feeder for the Laser Cladding process using Functionally Graded Materials. The powder feeder will transfer the FGM to the Laser nozzle for the deposition and experimentation. Moreover, the feeder will serve as the pioneer in the Laser Material Processing Operations using FGM’s in Pakistan.

Key Words: Laser Cladding, Multi Powder Hopper, Manufacturing, Modular Design, Powder Flow Rate, Bulk Density

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CHAPTER 1 INTRODUCTION

1.1. Introduction

Laser Material Processing, as contrary to the conventional processes, made the foundation for the high precision and tight tolerance operations in the manufacturing and repair industries. Laser Cladding is the subsidiary of Laser Material Processing which allows the deposition of the material upon the parent material (substrate) with the aid of laser beam. The advantages are precision operations with minimum Heat Affected Zone (HAZ) and high efficiency as compared to its counterparts. Laser Cladding process involves the knowledge and contributions from the fields of Robotics, CAD/CAM, Controls, Instrumentation and Powder Metallurgy. Powder Injection method used for the Laser Cladding process proves to be most efficient due to its controllability and minimum loss of surplus material.

Functionally Graded Materials (FGMs) are the recently developed specialized materials having the variability in their composition, porosity and microstructures across the applied length or volume. This variation allows the use of these materials in complex operating conditions, development of graded structural components and accustom products for the specific environments. Laser Cladding of Functionally Graded Materials is the novel field and immense research and development is under progress to develop the mechanism for the FGM cladding through Lasers.

1.2. Background

Since the invention of Lasers in 1960's, the implementation of laser technology in the field of material processing and manufacturing had been the goal. So far, Laser Material Processing Methods enables the manufacturers to develop products with high accuracy and tight tolerances and without the limitation of material specifications. However, researches are being underway to incorporate the Laser Cladding technology with the Functionally Graded Materials. In Pakistan, the use of Laser Technologies is limited to certain public-sector organizations due to its high operation and maintenance costs. Keeping this in the view, the aim of the research is aimed to develop the economical and efficient powder injection systems for the Laser Cladding processes to contribute towards the prosperity of Pakistan in Laser Technologies.

1.3. Scope of Work

The aim of the research is to develop the novel powder feeder for the laser cladding process using FGMs. The feeder will be able to accommodate three variants of metallic powders and can vary their concentration runtime during laser cladding operation. The feeder will be incorporated by the indigenously developed control system to control the powder flow rate of each powder variant. The development process and material selection should be done using the most viable manufacturing sources available in Pakistan to make the feeder economical and easily reproducible. Verification of the feeder design would be accepted by performing extensive experiments to conform the laser cladding operation. Above all of these, the developed multi powder hopper (MPH) feeder should be able to incorporate in the Pakistan Industry to contribute towards the betterment and optimization of local engineering works and maintenance.

1.4. Methodology

In this research, the multi powder feeder is designed and developed for the Laser Cladding process for the Functionally Graded Materials. To design the powder feeder, all the parameters involving Design for Manufacture, Design for Assembly and the powder flow dynamics are incorporated. Moreover, the study of intuitive instrumentation-based control system also taken into consideration to design the economical and effective control system for the feeder.

1.5. Summary

The development of novel multi powder feeder is based upon the pre-knowledge of design and fluid parameters for the efficient and effective powder feeder for the Laser Cladding process. All the research work is completed before the design process to develop the economical and durable multi powder feeder.

CHAPTER 2 LITERATURE REVIEW

2.1 LASER

LASER is the term widely used in engineering and sciences research since its discovery in 1960. It is the abbreviation of "Light Amplification by Stimulated Emission of Radiation". This term was first proposed by the Schawlow and Townes after their extensive analytical calculations lead to the famous "Schawlow-Townes Equation".

Figure 1: Laser Light

Since its discovery, lasers were extensively used various fields ranging from surgical instruments, military equipment, mechanical fabrication and machining, robotics, material processing and many more. Lasers are the primary candidates for the flexible manufacturing system (FMS) as a single laser can perform multiple operations if power density and interaction time are manipulated.

2.2 Basic Laser Principle

Lasers operation is based upon the stimulated emission phenomenon predicted by the Einstein in 1916. He analyzed in the radiation process the bombardment of photons on certain excited species and emission of the excited energy as the consequence. the excited energy, consists of the stimulated photons, were moving in the same direction as of the initial photons and were in phase with them.

In the light of above principle, not every material can emit such photons. The materials having more atoms in the excited state than in the lower energy state, to allow amplification instead of absorption, can qualify for the allowable materials. Types of materials/medium available for the laser emission are carbon dioxide (CO_2), carbon monoxide (CO), neodymium-doped yttrium aluminum garnet (YAG; Nd:YAG), neodymium glass (Nd:glass), ytterbium-doped YAG (Yb:YAG), erbium-doped YAG (Er:YAG),excimer(KrF,ArF,XeCl)

2.3 Components of Laser

To achieve the laser operation successfully, following three components must be present

1. Active Medium
2. Pumping Source
3. Optical Resonator

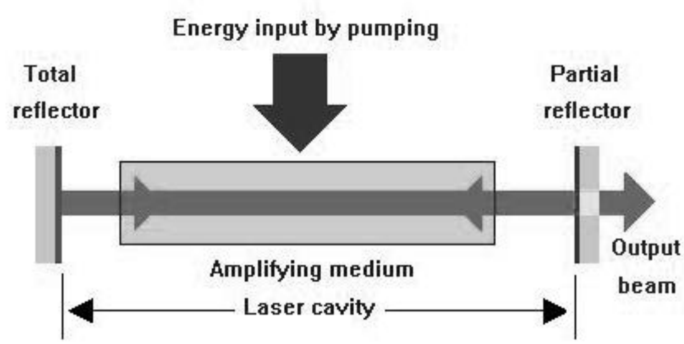

Figure 2: Basic Components of Laser

Active medium is the main module of laser. It consists of one of those types of materials listed in above section. As far as the state of the active medium is concerned, it can be either be solid, liquid or gas. Active medium is responsible for the emission of photons due to its excited nature. Pumping source can be described as the switch which will serve as the amplification of pre-excited atoms of the active medium to exhibit emission of photons. Pumping source can be of any type which can be used for desired purpose. Pumping source can be a flash lamp, electrons, chemical reaction, ions beams, X-ray beams or another laser source. One of the main parameters of the lasers is the output Power. Output Powder will determine the undergoing operation results. The output power of the laser (emitting photons) will be proportional to the output power of pumping source or excitation level of active medium. Increasing any of those parameters will increase the output power of laser.

Just as important active medium and pumping source is, the optical resonator is equally important. A optical resonator is responsible for the reflection of photon beams to amplify the final output. A optical resonator is the chamber, which houses the active medium, having 100 % reflective surface at one end and partially reflective surface with transmitting hole at other end. Optical resonator causes the generated beam to reflect continuously. The threshold of lasing is achieved when the gain from the reflection equals the losses occurs during the amplification process. Through the transmitting end, there is an output path for the beam from where the amplified and excited beam leaves the chamber. The output beam from the transmitting end is monochromatic and unidirectional.

2.4 Basic Characteristics of Lasers

The basic characteristics of a laser beam which can be beneficial of various beam differentiation and operation requirements are

1. Wavelength
2. Coherence
3. Power Distribution or Mode Diameter
4. Polarization

2.4.1 Wavelength

Wavelength of the laser is the most pivotal feature for the Laser differentiation. The wavelength is defined by the distance between the two adjacent crests or the troughs of the generated wave. This can be differed due to several reasons such as the medium resistance, the emission process, the emitting medium state and characteristics. Mostly, this differentiation is based upon the emitting molecules motion due to various transitions which take place during the stimulated emission. Table shows the various wavelengths of the most lasers used in the material processing and medical applications.

Table 1: List of Various Lasers and their respective wavelengths

Laser Type	Principle Wavelength (µm)
Carbon Dioxide Lasers	9.4
Carbon Monoxide Lasers	5.4
Dye Lasers	0.3 – 1.1
Free Electron Lasers	0.1 – 12.0
Nd:Y AG Lasers	1.064
Argon Lasers	0.4880
AlGaN Diode Lasers	0.38 - 0.45
Excimer Lasers	0.157
Helium-Cadmium Lasers	0.4416

2.4.2 Coherence

Coherence is the wave characteristic defining the long chain of emitting radiations providing the continuous wave patterns. Laser have this specific characteristic available in all the variants sue to its generation mechanism. The discharge chamber allows the emitted radiation from the active medium to oscillate which results the high energy short wavelength continuous waveform. However, the pulsed Lasing options are also developed for the high energy short pulses.

2.4.3 Power Distribution or Mode Diameter

The discharge chamber geometry plays the vital role in the lasing characteristics of the active medium. The chamber has the total reflective surface at one end and partial reflective surface at another which constitutes the optical oscillator. The two and forth movement of the radiations in the oscillator results in the generation of the standing electromagnetic waves in the chamber. The interference of these standing electromagnetic waves creates the transverse standing wave which emits from the discharge chamber classifies the mode structure of the beam.

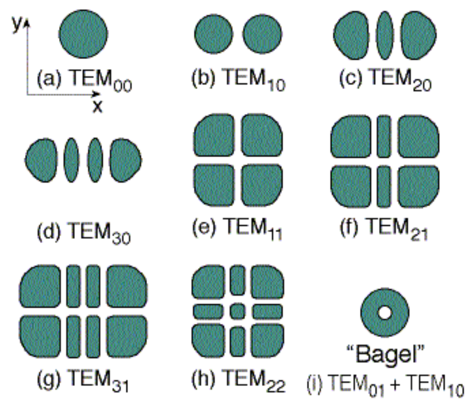

Figure 3: Various Transverse Energy Modes of Beam

These transverse standing waves mode patterns are classified by the "Transverse Energy Mode" (TEM_{plq}) where p is the number of radial zero fields, l is the number of angular zero fields and q is the number of longitudinal zero fields. The dependence intensity of the TEM upon lasing characteristic can be assessed by knowing that higher the order of the TEM, the more difficult to focus the laser beam to fine spot i.e. the beam sharpness majorly depends upon the transverse energy mode.

2.4.4 Polarization

As discussed in the previous section that the continuous oscillation of the emitted radiations generates the standing electromagnetic wave and then subsequently the standing transverse wave which determines the mode structure of the beam. The electromagnetic properties polarized the radiation and thus the Polarization characteristic has the major contribution in the laser operations and processes. Although, as other characteristics have some positive influence upon the laser processes, Polarization is somewhat contradictory. The polarized beam will affect the laser processes mainly the material processing techniques where the factors of accuracy, sharpness and linearity is involved. Hence, the measures were adopted to reduce the polarization of the emitted laser beams. The most used technique among others is the curved optical oscillator in the discharge chamber. In this method, the side-end reflectors inside the discharge chamber made in the curved fashion to change the overall travelling of certain beams. That will affect the overall interferences and the phenomenon of the polarization could be delayed.

2.5 Types of Lasers

Depending upon the type of active medium and pumping source, Lasers are classified into four broad categories.

1. Solid State Lasers
2. Gas Lasers
3. Dye Lasers
4. Free Electron Lasers

2.5.1 Solid State Lasers

As the name suggests, solid state lasers have the active medium in the solid form. Normally, the active medium rests inside the dielectric crystals or a glass. Active medium in the solid form means that the depreciation rate of the active medium is low as compared to the gaseous mediums and as a result, the life span of the solid-state lasers are generally higher than their counterpart gas lasers. Moreover, the solid medium has the tendency to emit high energy pulses (Q switching process) that are generally not in the case of gas lasers.

Solid States Lasers have various doping of active mediums, but the most available lasers are Neodymium doped Ytrrium Aluminum Garnet (Nd-YAG) Lasers, Erbium-doped Yttrium Aluminum Garnet (Er-YAG) Lasers and Ytterbium-doped Yttrium Aluminum Garnet (Yb-YAG) Lasers.

2.5.1.1 Neodymium doped Yttrium Aluminum Garnet (Nd-YAG) Lasers

Nd-YAG lasers are developed by doping Nd+3 ions into the Y3Al5O12 crystal. This doped active medium is pumped using the flash lamp as a pumping source. Pumping source excite the Nd ions to the metastable region from which they release the energy in the form of photons and travel to the terminal region.

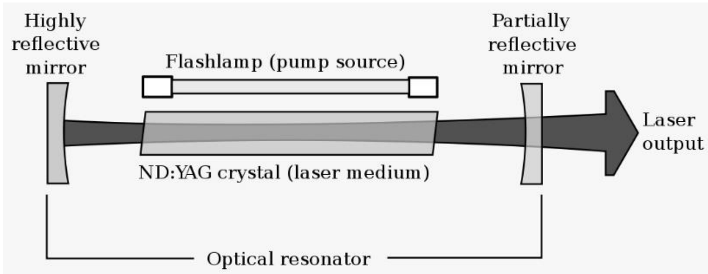

Figure 4: Nd:YAG Laser

The primary issue in the operation of the Nd-YAG laser is that it absorbed most of the heat from the pumping source to heat up instead of exciting itself. That causes a lot of problems during continuous operation of this laser. Water cooled tubes are attached to the laser chamber for cooling purposes. Furthermore, this cooling process also helps to cool down the ions to the ground region. As far as the efficiency goes, Nd-YAG laser has the quantum efficiency in the range of 30% to 50%. The maximum power output through this combination is 400W per 100 mm length of YAG rod. Above that, beam distortion occurs and severe heating of the medium could also come into play.

2.5.1.2 Neodymium Glass Lasers

This type of lasers has the Nd+3 ions doped into the Glass, as depicts in the laser title, instead of YAG crystals in Nd-YAG Lasers. Adoption of this combination has its own pros and cons. The pros include better energy conversion in glass than YAG crystals. Neodymium Glass Lasers are more prone to burst mode operation than its counterpart. The cons includes the severe cooling problems owing to the poor conductivity of glass. So, this laser requires more intense cooling system as compared to Nd-YAG Lasers.

2.5.1.3 Diode Pumped Solid State Lasers

As the name suggests, these types of lasers used the diodes as the pumping source instead of flash lamps. The use of diodes in the lasers were required as flash lamps were not performing to the optimal level and causes a lot of issues. One of the main reasons for shifting to diodes is that only few amounts of power from the flash lamps were contributing towards the absorption into Nd+3 ions and emission of photons. Rest of the energy causes the active medium to heat up quickly resulting in the short life span and beam distortion upon continuous usage. Moreover, operating requirements for the flash lamps were way too high as compared to the output generated by them. Diodes, in comparison, are way too energy efficient. The wall plug efficiency of diode Is rated as 30%-50% and the emission is the range of 808 nm. Diode Pumped Lasers have the higher beam propagation ratio i.e. M2 (M2 or beam propagation ratio is the value that shows that how much near the emitted beam is equal to fundamental transverse gaussian mode TEM00 beam). The applications of diode solid state lasers will certainly be the areas where the energy efficiency and low cooling requirements are preferred.

2.5.1.4 Disc Lasers

Disc lasers are the types of solid state lasers in which the active medium is in the form of disc. The YAG crystal, in the form of disc, is doped with the Ytterbium or Neodymium ions and diodes are used as the pumping source to emit the high quality and sharp laser beam up to the wavelength of 1.03 µm. the working procedure of the disc lasers makes them a strong candidate for the high output rate with continuous usage. Maximum amount of the emission is done through the one side of the disc and the other side of the disc is attached with the heat sink area. That assembly make the superior cooling possible for the active medium and the lasers can be operated for much longer time without compromising much on the output as compared to other solid-state lasers.

2.5.1.5 Semiconductor Lasers

Due to advancement in laser technology, several methods are used now a day to generate the required output laser beam. One of them is the semiconductor. In the previous topics, the use of semiconductor as the pumping source is discussed but the same can also be used as the active medium to emit the photons in the range of 0.38 to 30 µm.

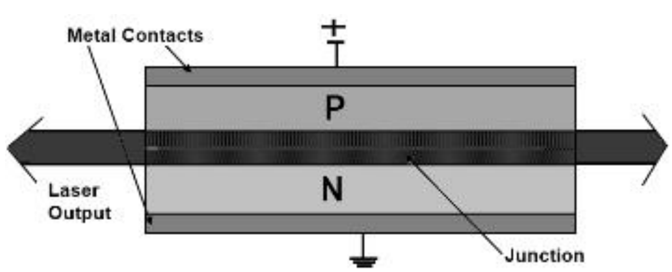

Figure 5: Basic Semiconductor Laser Principle

This high range availability in the semiconductor lasers makes them the ideal choice for the laser operations. Moreover, the use of diode as the active medium as well as the pumping source makes this type of lasers much more efficient, reliable, compact and with quick modulation response. The emission of the photons beams in this broad range is made possible due to the design of the diode. The diode has the positive region (holes) and the negative region (electrons) separated by the P-N Junction. As the energy supplied to the negative region from the pumping source, the electrons get excited and started to move towards positive regions by emitting photonic energy at the junction. As the negative and positive regions of the diodes could be increased or decreased, the long range of output energy levels can be obtained. Diodes are famously known for the efficient operation and in the lasers, the semiconductor lasers have the wall plug efficiency of 50%. The applications of the semiconductor lasers range from heating to welding of various materials. Table shows the various types of semiconductor lasers and their output beam wavelength.

Table 2: Different semiconductor materials and their wavelengths

Type of Semiconductor Material	Emission Wavelength (μm)
AlGaAs/AlGaAs/GaAs	0.7-0.9
GaInPAs/InP/InP	1.2-1.6
GaInP/AlGaInP/GaAs	0.66-0.69
AlGaAsSb/AlGaAsSb/GaSb	1.1-1.7
GaInN/AlGaN/sapphire	0.38-0.45
PbSnTe/PbSnSeTe/PbTe	6-30
PbSSe/PbS/PbS	4-7
PbEuTe/PbEuTe/PbTe	3-6
ZnCdSe/ZnSSe/GaAs	≈ 0.5

2.5.2 Dye Lasers

In dye lasers, the large molecules of dyes, weighing around 700-1000 molecular weight, are used for the laser emissions. They have the lasing action working as the pumping source as well. The eminent factor which distinguish the Dye laser from its counterpart is this can be heavily tunable. Changing the intensity of the pumping laser can contribute towards the emission of long range of laser wavelengths. Moreover, the concentration of the dye used as the active medium can also be modified to the desired output. The applications of these tunable lasers can be ranges from isotope separation in the material processing to the laser cooling and optical trapping.

2.5.3 Free-Electron Lasers

The operation of the Free-Electron Laser depends upon the Synchrotron Radiation. Synchrotron Radiations are the electron emissions whenever the electron changes or forces to change its motion direction. This emission is generated by the help of the turning magnets installed in the laser equipment. These magnets are responsible for the change in electron path during their course towards magnetic wiggler to emit photons. The main advantage of using these process is the generation of various spectral emissions. The particular electron motion generates the corresponding particular emission and as a result, Free-Electron Lasers are also termed as the Rainbow Lasers due to their specific characteristic of generating various spectral emissions.

2.5.4 Gas Lasers

Gas Lasers are the most widely used lasers in the material processing and medical industries. Their wide range of usage in addition to their ease of operation of widely available active mediums makes them the priority candidate for the lasing operations. the main types of the Gas Lasers are

1. Carbon Dioxide (CO_2) Lasers
2. Carbon Monoxide (CO) Lasers
3. Excimer Lasers

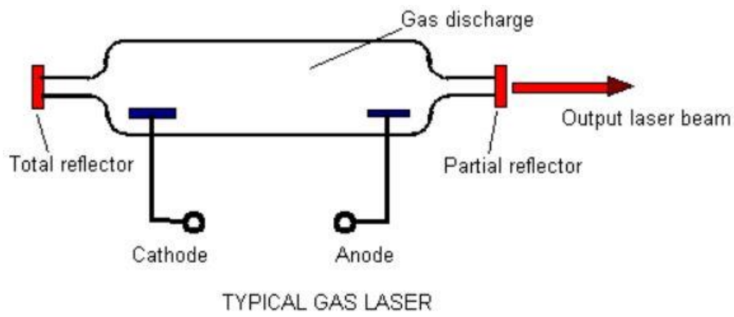

Figure 6: Basic Composition of a Gas Laser

2.5.4.1 Carbon Dioxide (CO_2) Lasers

Carbon Dioxide Lasers are one of the most used lasers in the industries right now. They use the carbon dioxide (CO2) gas as the active medium. These lasers work on the principle of plasma radiations. The electric discharge is used as the pumping source. The electric discharge can be of Direct Current (DC), Alternating Current (AC) and Radio Frequency (RF) discharges. This electric discharge converts the CO2 gas into the plasma state which is very high energy unstable region. The high energy molecules in the excited state release the energy in the form of radiations. These radiations reflect two and forth in the lasing chamber and in this way, strikes other molecules which are in the low energy states to take them to high energy levels. This process of transferring lower energy state molecules to the high energy creates the population inversion phenomenon and a point reaches when the number of high energy state molecules are more than the lower state molecules. This is the ideal scenario for the lasing action. All the radiations emitted by the excited molecules reflect in the chamber and emit out of the discharge chamber with the wavelength of 10.6 µm.

Though the Carbon Dioxide Lasers are thought to be using CO2 gas entirely as the active medium, it will be come to surprise that the proportion of the CO2 gas in the active medium is only around 10%. A major contribution in the proportion is done by Helium (He) gas which is around 78% and around 12% is utilized by the Nitrogen (N2) gas. The Helium gas is incorporated into the medium to provide sufficient stabilization to the plasma state CO2 molecules. As Helium gas is the noble gas, it would also be providing the required shielding and non-reactiveness of the excited CO2 molecules with the discharge chamber. The role of Nitrogen (N2) gas in the mixture is a bit vital as the N2 gas contributed itself as the catalyst for the lower state CO2 molecules. The lower proportion of the CO_2 gas in the medium raised the probability regarding non-exciting molecules in the mixture. The N_2 gas gets excited and emits radiations to excite those remaining lower state molecules. In that case, Nitrogen gas acts as the catalyst in the excitation process to streamline the excitation and emission process. Moreover, the usage of the N_2 gas in the medium also contributes towards the long life of the CO_2 lasers.

As with all other lasers, the cooling mechanism holds an essential role in the efficient and effective operation of the CO_2 lasers. The cooling requirements for the CO_2 lasers are based upon the various categories of the CO_2 lasers. CO_2 lasers can be used as the Slow Flow Lasers, Fast Axial Flow Lasers and the Transverse Flow Lasers. These categories differ in the operation techniques and the optimal output requirements. The Slow Flow Lasers uses the wall cavity coolant gas which flow around the chamber. Fast Axial Flow Lasers uses the low-pressure coolant gas which circulates at higher rates around the discharge chamber. Transverse Flow Lasers, in similar fashion, uses the low-pressure coolant gases which moves in the higher rates around the discharge chamber to cool down the active medium for long life span.

2.5.4.2 Carbon Monoxide (CO) Lasers

These lasers come under the constituency of Gas Lasers which means that the design and operation procedures would be approximately similar to that of Carbon Dioxide Lasers. Using the Carbon Monoxide (CO) gas as the active medium and the electrical discharges as the pumping source, the CO laser's operation differs to that of CO_2 lasers in the emitted radiations and the operating accessories. The diverging point from the CO_2 lasers are the immense cooling requirements as compared to the CO_2 lasers. However, the emitting radiation of 5.4 µm is very precise and open the gates for their applications in hydraulic processes and medical processes owing to its optimal absorption in water.

2.5.4.3 Excimer Lasers

Excimer lasers get their name from the combination of two words i.e. Excited and Dimer. Excimer Lasers are the slightly among the distinct categories of the Gas Lasers due to their design and operating ranges. The Excimer Lasers uses the excited dimer molecules in the excited states as the active medium to emit the photons in the ranges of 0.4 nm. The active medium consists of various gases proportion to create the optimal solution for the requirements. This is the major reason behind the usage of Excimer Lasers in various circumstances owing to their customizable active medium. The major and prior contributor gases in the excimer solution are the Halogen, Argon, Krypton, Xeon, Helium and Neon Gas. As majority of the proportion is covered by the noble gases, the Excimer lasers are often regarded as the Noble Lasers. The design of the Excimer Lasers does not include the oscillators in the cavity due to its high energy emissions in natural aspiration. Various Types of Excimer Mixtures are mentioned in the Table

Table 3: Various Excimer mixtures and their respective wavelengths

Excimer Mixture	**Emitted Wavelength (μm)**
F2	158
ArF	193
KrCl	222
XeCl	308
XeF	354
KrF	248

2.6 Applications of Lasers

Since the invention of Lasers in 1960, the applications of lasers have been widely increased. Now a day, the applications of lasers can be classified in to three broad categories.

1. Application in Optical Industry
2. Applications in Power Industry
3. Applications in Material Processing

In a bird eye view, the applications of the lasers cover the subsequent areas

1. Length Measurement
2. Velocity Measurement
3. Holography
4. Speckle Interferometry
5. Material Inspection
6. Pollution Detection
7. Analytical Techniques

8. Data Recording

2.6.1 Laser Applications in Material Processing

Lasers have been in use for the material processing jobs for long ago. They have an excellent energy to accuracy ratio which makes them the first choice for the precision and complex processing requirements. Throughout this wide regime of fields, applications of lasers, not limited to, includes:

1. Laser Cladding
2. Laser Cutting
3. Laser Welding
4. Material Shaping
5. Rapid Solidification
6. Laser Heat Treatment
7. Laser Processing of Semiconductor
8. Laser Drilling
9. Laser Piercing

2.6.1.1 Laser Cladding

Laser Cladding is an inter-disciplinary process merging Laser Technology, Computer Aided Design / Manufacturing (CAD/CAM), Optical Science, Robotics, Instrumentation and Control as well as Powder Metallurgy.

Laser Cladding is the subsidiary of the Additive Manufacturing process in which laser beam is used to deposit the layer of material upon the surface of another material. This process is under operation for many years through Plasma Spraying and Arc Welding. However, the basic difference of using lasers instead of Plasma and Electric discharge is the requirement of better coating, minimum dilution, minimal distortion and better surface quality. These are few reasons that the Laser Cladding is also termed as the Laser Coating, Laser Powder Deposition and Laser Surfacing.

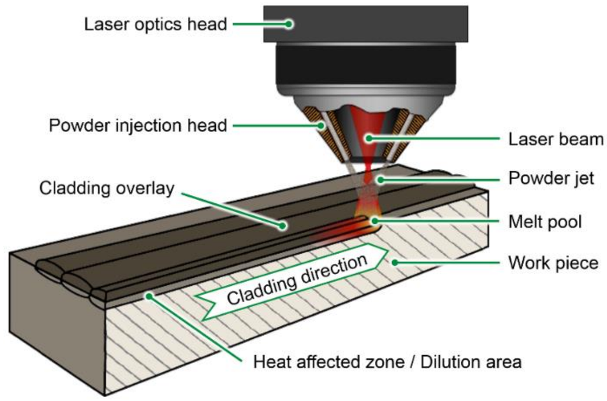

Figure 7: Laser Cladding Working Principle

In addition to the surface coating applications, Laser Cladding also contributes itself to Rapid Manufacturing / Prototyping. Rapid Prototyping (RP) is a feature of Additive Manufacturing Processes in which a product or item is manufacturing by addition of material layers instead of conventional machining processes which includes removal of material. The renowned characteristics of the RP process i.e. homogenous structure, enhanced mechanical properties, and one step production of complex properties are the unique properties of laser cladding. The major advantages of using laser cladding technique as the RP process are huge such as:

1. Production Time Reduction
2. Thermal Control Enhancement
3. Repairing of Parts
4. Functionally Graded Parts Production
5. Smart Structure Production

However, to execute the Laser Cladding process, the foremost requirement is the material availability for the laser to melt that and deposit down upon the parent surface. There are numerous ways in utilization but the prominent ones are:

1. Pre-Placed Powder
2. Wire Feed Powder
3. Injected Powder

Pre-placed powder is the one of the earliest method for the cladding and coating processes. In this method, the powder material is placed upon the parent surface and then the laser or the gas flame is used to melt and deposit that powder upon the surface. As it is seeming to be the ideal solution because it requires less machinery and hustle, but the disadvantage is the uncontrollable melting of the powder. the concentration of melted powder cannot be monitored and that results in poor surface finish and accuracy.

Wire feed Powder is the next step towards the innovation in material processing. The need of wire feed material originated when the parent surface area is not enough to hold the powder material for the processing. Wire feeding involves the development of the wire of the deposited material. The wire is placed at the target area and melted through laser beam or flame. This has resolved the concentration control problem arose in the pre-placed powder technique but holding the wire too close of the high energy / temperature area was not proved safe and therefore the need of any new technique of power placement and transfer originated to not only assist the powder cladding processes but also to control the concentration of the ejected powder.

Powder Injection method is widely the most trusted and used technique in the laser cladding processes. It involves the powder transfer to the laser beam nozzle with the help of the powder feeders to facilitate and monitor powder flow concentration.

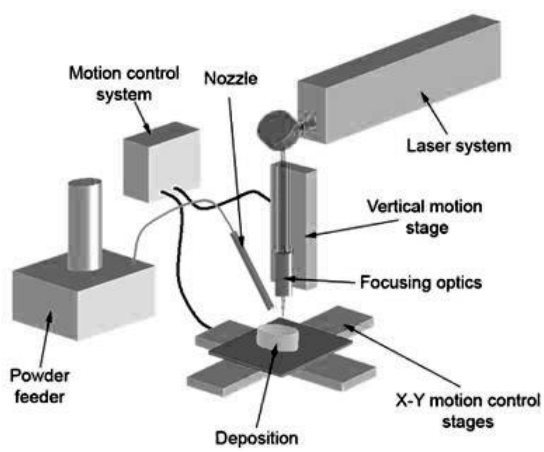

Figure 8: Laser Cladding Through Powder Injection

As the meeting point of the laser and powder is at the beam nozzle, the design of nozzle will contribute towards the flow of incoming powder flow and the laser beam. For this matter, the configuration of the nozzles is of two types.

1. Lateral Nozzle
2. Co-axial Nozzle

Lateral Nozzle design facilitates the delivery of the powder to the melt pool created by the laser beam. In Lateral Nozzle, the laser beam propagates vertically and the powder deliver in lateral direction. Apart from many pros, Lateral Nozzle don't have enough flexibility for the three-dimension processes.

Co-axial Nozzle is the advanced and efficient nozzle design in which the powder and laser beam converges inside the nozzle and propagates in parallel. The powder comes from the sideways and laser beam from the center and they interact at the center of nozzle. This improves the material deposition rate and, as contrary to the Lateral Nozzle, Co-axial Nozzle has the flexibility for three-dimension processing.

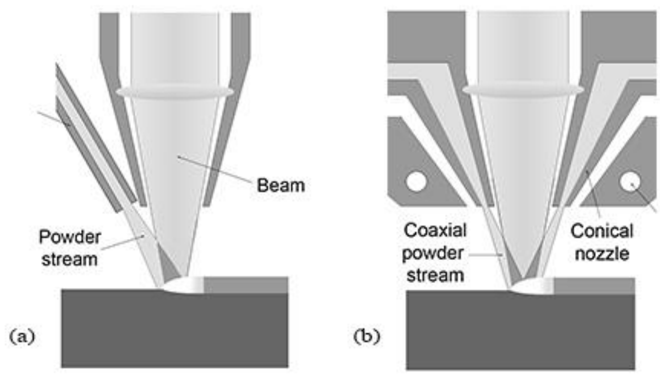

Figure 9: Types of Powder Injector Nozzles (a) Lateral (b) Co-axial

2.6.1.2 Applications of Laser Cladding

Laser Cladding process has proved itself as the better and efficient alternative to the conventional coating methods due to its convincing benefits. It offers a fast operation with better material properties. It can also contribute towards homogenous and critical structure productions. Laser Cladding has the instant impact upon the small batch production as it can rapid manufacture the prototypes for final approval and testing. Furthermore, this process is capable of the production of wide range of materials due to formation of various alloys through powder deposition. However, the major areas of the applications for the Laser Cladding processes are:

1. Prototype Production
2. Requirement of Better Post Thermal Treatment
3. Deposition of Material for Substrate Repair
4. Component Embedment

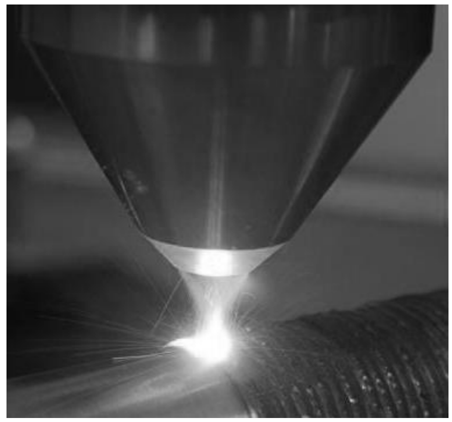

Figure 10: Deposition of Metal Coating upon a pipe using Co-axial Laser Cladding process

2.7 Powder Feeders

As mentioned in the earlier sections, Laser Cladding process is performed through various combinations. One of them is powder injection technique which involves the use of powder feeders for the powder transportation. Powder Feeders are the storage devices used for the storage, protection and transportation of powders whenever required through the attached channels.

As far as the laser cladding is concerned, the powder feeders have the significant role in the transportation of powder to the melt pool. Since its introduction, there are numerous types and shapes of powder feeders developed to fulfill generic or customized requirements. However, the types and shapes of the powder feeders revolve around the following categories:

1. Gravity Based Powder Feeder
2. Mechanical Wheel Powder Feeder
3. Fluidized-Bed Powder Feeder
4. Vibrating Powder Feeder

Moreover, the combination of either of the methods are also used often to achieve desired outputs.

2.7.1 Gravity Based Powder Feeder

The basic working principle of these feeders is the gravitational force which is responsible for the downward flow of powder. The primary factors which affect the feeding process are the particle size and the viscosity parameters.

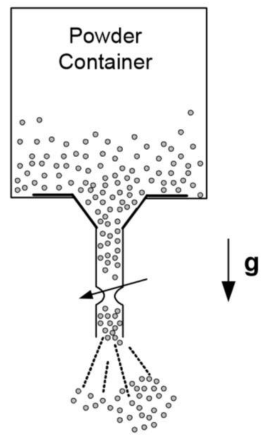

Figure 11: Gravity Based Powder Feeder

The size of the orifice will determine the required powder flow from the feeder. Although the flow is based upon particle weight, it can be optimized and controlled by the addition of metering device i.e. metering wheel or disc.

2.7.2 Mechanical Wheel Powder Feeder

In a Mechanical Wheel Powder Feeder, the powder flow is done with the help of a mechanical screw. This is the reason these feeders are also called mechanical screw powder feeder. The screw used in this feeder has a pitch with varying diameter across its length. This helps to transport the powder from the hopper to the required destination.

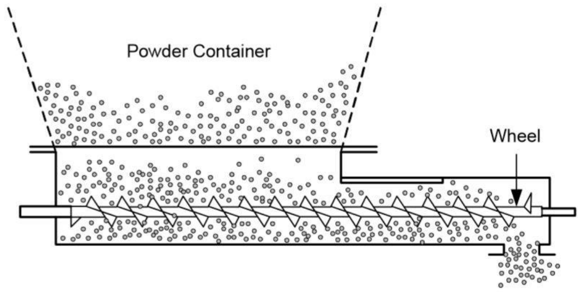

Figure 12: Mechanical Screw Powder Feeder

This arrangement permits the feeder to transport large amount of powder. Since the screw rotation is solely responsible for the powder flow, the rotation is directly proportional to the amount of powder required at the other end.

2.7.3 Fluidized-Bed Powder Feeder

This type of powder feeder operates on the fluidic principle. A predetermined quantity of gas is introduced in the close hopper and that makes the powder fluidized. This fluidized powder is then transferred to the carrier gas through the powder pickup tube which transfer the powder to the required destination. This type of feeder has no mechanical or moving part which reduces the maintenance and repair cost.

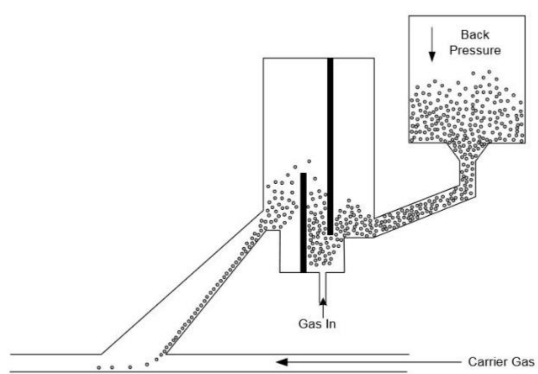

Figure 13: Fluidized Bed Powder Feeder

2.7.4 Vibratory-Based Powder Feeder

Vibratory-Based Powder Feeder works on the powder transfer through vibration of transfer plates. The stored powder in the hopper moves downwards due to gravitational force upon the flat-bottomed tray. The tray is attached to the forcing mechanism which vibrates the tray so that the powder started flowing further downwards, overcoming viscosity, to the required destination.

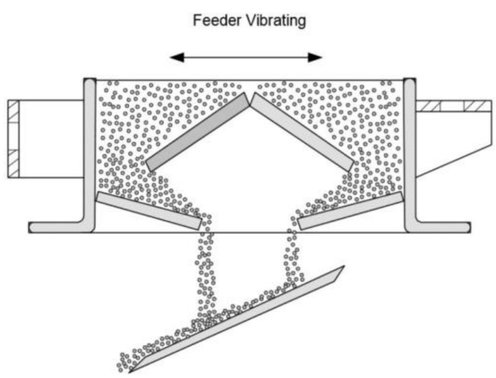

Figure 14: Vibratory Based Powder Feeder

The vibration should be controlled to monitor the powder flow rate. The efficiency of the feeder could be enhanced by using several trays attached to the vibrating mechanism to operate more efficiently and effectively.

2.8 Metallic Powder

Metallic Powder is the most essential part of the cladding process. It will get deposited upon the substrate after interacting with the laser. The physical and chemical properties of the selected powder are very crucial for the selection as this will affect the overall process and the clad layer. Moreover, the viscosity and particle size of the selected sample will also be known before initiating the cladding process.

2.8.1 Flow Properties

The powder stream consists of small particles (mostly in the size of micrometers) which moves along one another and the inter particle friction will constitute towards the overall flow of the powder stream. So, the flow properties of the powder stream must be known to some extent to predict the final outcome. Factors which will affect the flow of the powder are:

1. Bulk Density
2. Angle of Repose
3. Avalanching
4. Rat Holing

Bulk Density is defined by the mass of the total particles in the container divided by the total occupied volume. The total volume comprises of particle volume, inter-particle void volume and internal pore volume.

Angle of Repose is the angle at which the pre-placed powder particles stick to their position without any adhesive or binder and restrict their flow downwards. This property is essential for the determination of powder viscosity and inter particle friction.

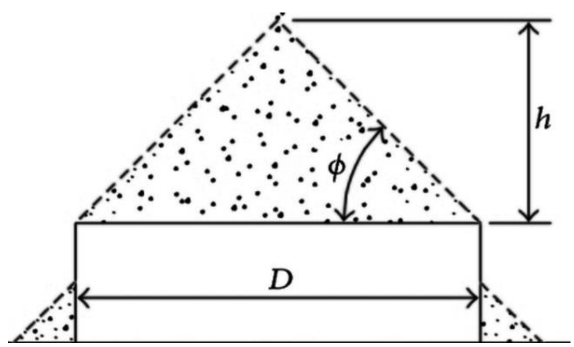

Figure 15: Angle of Repose

Avalanching is the property of granules defined by the rapid flow down a sloping surface. This is usually generated by the mechanical failure inside the powder stream. This property contributes towards the flowability and viscosity of the powder stream.

Rat Holing is the major obstacle in any powder flow scenario especially powder flow from the storage area. In this case, the powder situated in the central area (parallel to hole axis) moves outwards quickly than the powder at the sides of the container. This cause the under flow of the powder and the major volume of powder is stuck resulting in loss. This situation can be overcome by installing the stirrer inside the container which will ensure the continuous rotation of the powder and reduce blockage.

2.9 Functionally Graded Materials (FGMs)

Functionally Graded Materials (FGMs) are the specialized and customized materials developed that have varying composition over the entire bulk volume. These materials fulfill the vacuum present in the material processing areas where the single or continuous composition aren't fulfilling the optimal requirements. FGMs are designed to have variable composition, chemical properties, porosity, and microstructure across the length of deposition. Since their introduction, FGMs have developed themselves into every possible area of application. Today, FGMs are regarded as the prior input in the aerospace, automobile, defense, armory as well as in bio-medical processes.

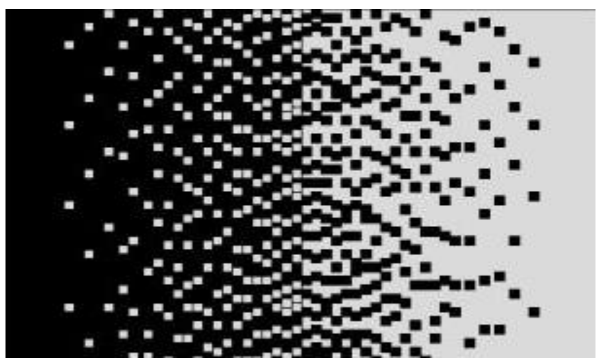

Figure 16: Functionally Graded Material (FGM)

Due to their wide range of applications and requirements, FGMs are categorized into three broad categories:

1. Compositional Gradient FGMs
2. Porosity Gradient FGMs
3. Microstructure Gradient FGMs

2.9.1 Compositional Graded FGMs

These are the FGMs having the variable composition of material across the entire length. This results in the changing chemical properties, physical properties, behavior and thermal properties.

This could be beneficial in the material processing areas where the deposition layer should have these variations across the deposited length to counter various expected situations.

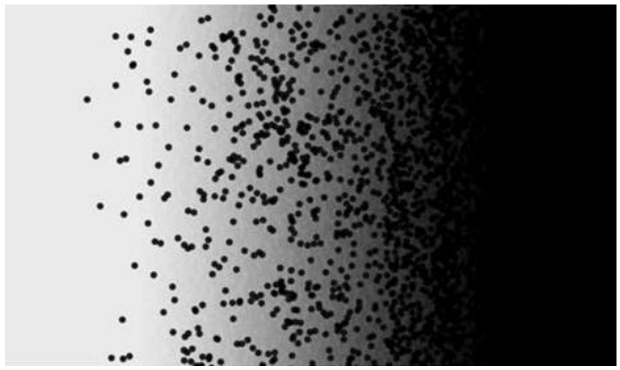

Figure 17: Compositional FGMs

The use of these materials cannot be predefined in certain areas as they can shape themselves accordingly. In material processing, Compositional FGMs can prove themselves to be the vital source for the structural repairs, surface hardening, structural strengths, and various resistive coatings to counter the variable circumstances.

2.9.2 Porosity Graded FGMs

Porosity Graded FGMs are the types of FGMs mostly used in the bio medical applications. These have the porosity as the variable factor across the spatial position of the bulk material. This porosity variations helps in the absorption of the shock from one face to another. Furthermore, thermal insulation, catalytic efficiency and electrical and thermal stresses relaxation are also the salient features of the porosity graded functionally graded materials. Moreover, this pores gradation also affects the tensile strength and Young's Modulus of the material.

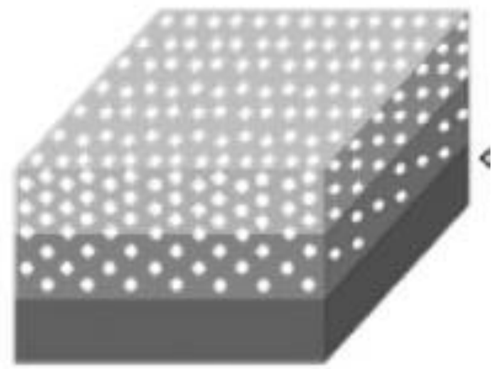

Figure 18: Porosity FGM

2.9.3 Microstructure Graded FGMs

This is the special type of FGMs in which the microstructures of the grains are altered in the bulk material volume. This doesn't require the addition of any other material into the final mixture as in the case of Compositional FGMs. Mostly, the microstructural variations in the material is achieved through the solidification process.

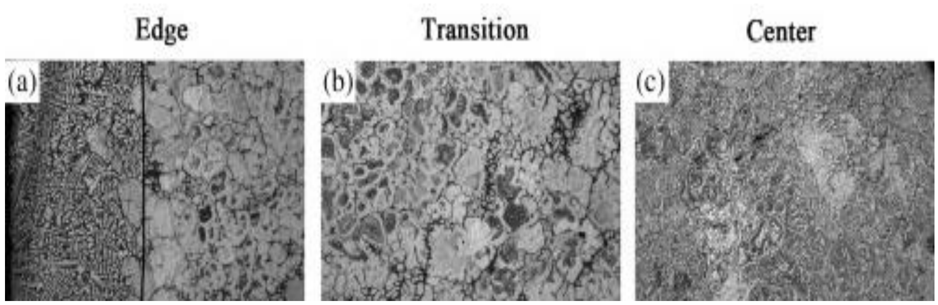

Figure 19: Microstructure FGM

Different areas of the material are allowed to cool down in different fashions to obtains variations in microstructures. Microstructure FGMs are used in the areas where a requirement of a harder surface for wear resistance and a tougher core for impact resistance. In most cases, the applications of these FGMs are in the manufacturing of turbines, bearings and shafts, cam or ring gear and case-hardened steels.

2.10 Applications of Functionally Graded Materials

As discussed in the previous sections, Functionally Graded Materials highly customized and specialized materials and that's why the scope of applications is widely spread in the material processing areas, medical applications, defense areas, automotive and aerospace parts and many more. Due to their varying nature, these materials have a much larger scope in the developments of components operating in the harsh operating conditions i.e. heat engine components, heat exchanger tubes, thermos-electric generators as well as electrical insulating applications.

Figure 20: Various Materials manufactured using FGMs (a) Impeller (b) Turbine Blades (c) Cam Ring

Since these materials are still in development phase, the high production costs of these materials limit their use in only complex and tight tolerance areas. However, with further research in the FGM development, the applications of these materials will be spread across the globe.

CHAPTER 3 DESIGN AND DEVELOPMENT

This chapter comprises of the procedures followed for the design and development of the multi powder feeder, its control system and the suction unit necessary for the powder transfer operation.

3.1 Methodology

Multi powder hopper feeder operates on the procedure of powder suction. Three hoppers installed in the feeder contains various metallic powders. The powder from the hoppers is transferred through the disk rotation mechanism. Spreader tubes assembled with the hoppers inside the disc housing transfers the powder to the rotating disc groove which feed to the suction end. Suction tubes, mounted inside the disc housing as spreader, acts as a catalyst to transfer powder from the disc housing to the powder mixing unit which further transfer mixture of powder to laser beam through connecting mechanism. The rotation of the discs is controlled by the control system operated from the GUI. The powder feed rate from each hopper is controlled by their respective disc rpm and hence the concentration of the individual powder in the mixture can be varied in a runtime environment through GUI. In order to avoid the powder clogging in the hopper, stirrers are mounted into the hoppers rotates at constant rpm

3.2 Design Procedure

Designing the multi powder hopper was the preliminary step towards its development and experimentation. A good and thoughtful design always contributed towards the successful development and assembly of various parts.

The complete design of the multi powder hopper was developed in Solid Edge ST8 CAD software. Design of the multi powder hopper is divided into following sub-categories

a. Basic Structure
b. Disc Housing
c. Hopper Design
d. Mixing Chamber
e. Control System
f. Suction Unit

3.2.1 Basic Structure

The basic structure of MPH consists of a steel frame with acrylic sheets covers bolted with the frame. The steel frame, made up of Mild Steel, is a structure of square angles of 18 mm having the thickness of 2 mm. The basic objective of the steel frame is to give an added strength to the structure as compared to the acrylic sheets.

The sheet covers used in the steel frame are of high strength acrylic glass. Acrylic is lighter than wood and glass and allows for internal visuals of components. The side walls sheets are of 15 mm thickness to effectively support the weight.

To conform the DFM and DFA criteria, all the glass sheets and steel frame are joined together with the help of bolts. DIN-912 M10x40 Allen Bolts are used to join all the parts together to form a coherent design.

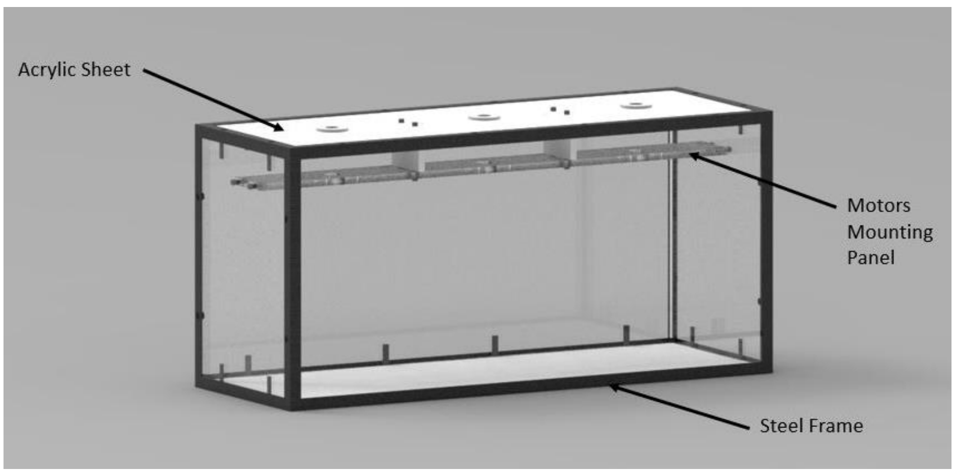

Figure 21: Basic Structure CAD

3.2.2 Disc Housing

Disc housing is the most critical part of the whole MPH feeder and for this matter, all the included components are thoroughly designed to conform the DFA principles. Disc Housing includes the following components.

i. Upper Cover
ii. Lower Cover
iii. Central Ring
iv. Disc
v. Disc Shaft
vi. Bearing
vii. Suction and Spreader tube

The upper cover of the housing is responsible for the attachment of Hopper and piping for the suction unit. The plate is an acrylic glass sheet of 10 mm thickness having the positioning for the hopper attachment, suction piping attachment and suction and spreader unit attachment. Spreader and suction units are attached to the upper cover through DIN-912 M4 Allen Bolts. The upper cover itself assembled to the disc housing through DIN-912 M4 Allen Bolts.

The lower cover of the housing is responsible for the attachment with top sheet of basic structure. The cover is an acrylic glass sheet of 10 mm thickness just as upper cover. It includes collar for the partial positioning of bearing. The lower cover assembles to the basic top sheet and disc housing through DIN-912 M4 Allen Bolts.

Central Ring of the housing is responsible for the accumulating all the components of the housing inside. It is an acrylic glass 220 mm ring having width of 50 mm. the central ring is attached to the upper and lower cover with DIN-912 M4 Allen Bolts.

Disc is the most indispensable component of the multi powder hopper feeder. The flawless operation of the disc contributes towards the overall efficient operation of the system. Disc is a 180mm diameter circular part made from aluminum. Disc is responsible for the powder transfer from the spreader tube connected to the hopper to the suction tube connected to the suction unit through piping. It has the groove upon its top surface to accommodate powder. The groove is a 5 mm in width and 3mm in depth. The positioning of the groove is such that it is concentric with the spreader and suction tube holes. Furthermore, it also has the collar on the bottom surface for the shaft positioning and holes for the shaft assembly through M4 countersink Philips screws.

Disc Shaft is responsible for the rotation of the disc for powder transfer mechanism. Shaft is a Stainless-Steel Rod with maximum diameter of 50 mm. the top collar of the shaft (50 mm diameter) attaches to the disc through M4 countersink Philips screws. The bottom end of the shaft has the diameter of 10 mm attached to the control system motor through coupling.

Bearing is responsible for the smooth rotation of the shaft and to hold the shaft firmly to lower the rotational friction and consequently less torque will be required to rotate the shaft. The Bearing used is the NTN 6004 ball bearing. The bearing resides in the collar between lower cover and the top sheet of basic structure.

Suction and Spreader tubes are responsible for the transferring out and transferring in the powder to the housing assembly respectively. Suction tube is a glass acrylic tube of 40 mm diameter. Additionally, it has the tube extending out the housing assembly for the piping connection.

Spreader tube is an acrylic glass tube of 40 mm diameter. It has a collar to accommodate hopper and serves as the hopper housing for the powder transfer. Both have the curved section of 3 mm thick have the same curvature as the disc groove. That curve not only serves as the groove placement but also, it will block the powder to go backwards. Both suction and spreader tube assemble with the upper cover, as mentioned earlier, with the DIN-912 M4 Allen Bolts.

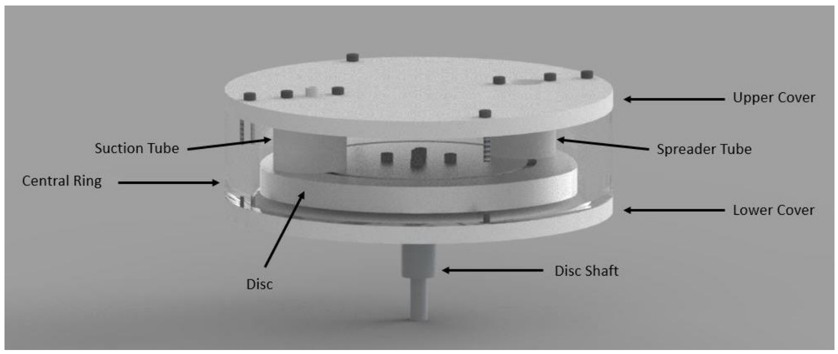

Figure 22: Disc Housing CAD

3.2.3 Hopper Design

Hoppers are the storage components of the multi powder hopper feeder. Hoppers are used to store and supply metallic powder while operation of the feeder. Hoppers resides in the spreader tube through upper cover of the disc housing assembly. Metallic powder, stored in the hopper, travel to the disc groove through spreader tube.

It is essential to design the hoppers to minimize the powder clogging inside them. To cop up with that, Hopper assembly consists of five parts.

a. Upper part
b. Lower part
c. Hopper Lid
d. Hopper Stirrer
e. Hopper Stirrer Motor

Upper part is the container shape section of 100 mm outer diameter. There is a threaded portion to place the hopper lid and the lower threaded collar for the connection with the lower part of the hopper.

The lower part of the hopper is the conical flask structure of glass acrylic having maximum diameter of 100 mm. It has the threaded collar at upper side to accommodate upper part of the hopper. The lower section of the part is a tube which will sit inside the spreader tube and serves as the hopper support as well as air seal for the powder flow. The 6-mm thick above the sitting section is the holding point of hopper on the upper cover of the disc housing assembly. It has the finite holes in which the DIN-912 M4 Allen Bolt head of the spreader tube resides and added to an additional support for the hopper.

Hopper lid is the protective cover upon the hopper as well as the mounting point for the hopper stirrer motor. It is of glass acrylic having 110 mm diameter. The internal side has the threaded portion to be placed upon the upper part of the hopper. The central hole is positioned for the coupling of stirrer and its motor shaft.

Hopper Stirrer is responsible for the mixing of metallic powder so that it couldn't clogged inside hopper during the operation. The stirrer is designed as the inversed pyramid structure from Stainless Steel having maximum diameter of 20 mm at the top section and 5 mm at the bottom. For the stirring mechanism, there are four stirrer blades, 45 degrees to each other and 10 mm apart. The reason of this is to have a full rotational connection between the blades and the powder and to have a more efficient stirring operation. The top section is responsible for the coupling point for the DC motor. The stirrer is galvanized to avoid any type of reaction with powder during operation as there is a strong concern of temperature increase during runtime operation due to friction between two metallic surfaces.

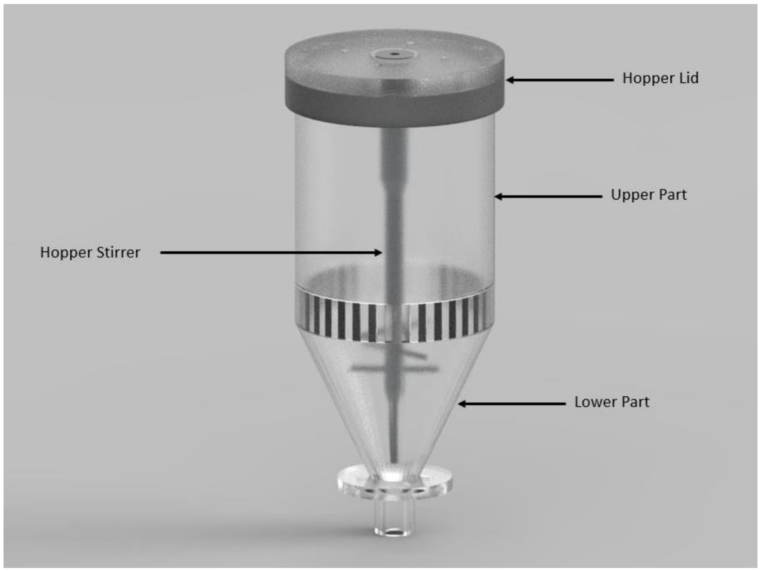

Figure 23: Hopper CAD

3.2.4 Mixing Chamber

Mixing chamber can be considered as the most essential part of the multi powder hopper feeder. The design of the mixing chamber must be as simple as possible and must comply all the required specifications of the powder mixing phenomenon. Any discrepancy in the mixing chamber will lead to improper mixing and non-homogenous results.

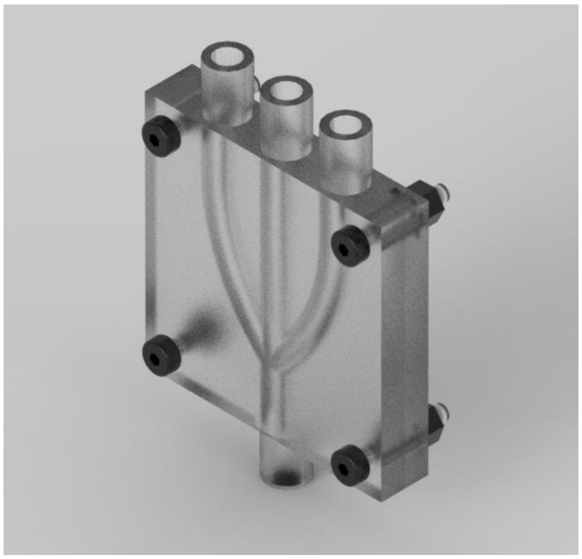

Figure 24: Mixing Chamber CAD

The mixing chamber developed for this feeder system is a glass acrylic 20 mm thick structure with embedded flow lines curves for the powder intake from all three suction tubes and one integrated out port towards the suction unit. This chamber is a structure joined through the DIN-912 M3 Allen Bolts.

3.2.5 Control System

Control system of the feeder comprises of the electronic components required for the instrumentation purposes. The fundamental components include

1. Control Panel Console
2. Graphical User Interface (GUI)
3. Micro-controller
4. DC motors
5. Power Unit
6. Micro-controller assisting modules

Figure 25 shows the schematic arrangement of the control system and Appendix includes the connection diagram of the control system

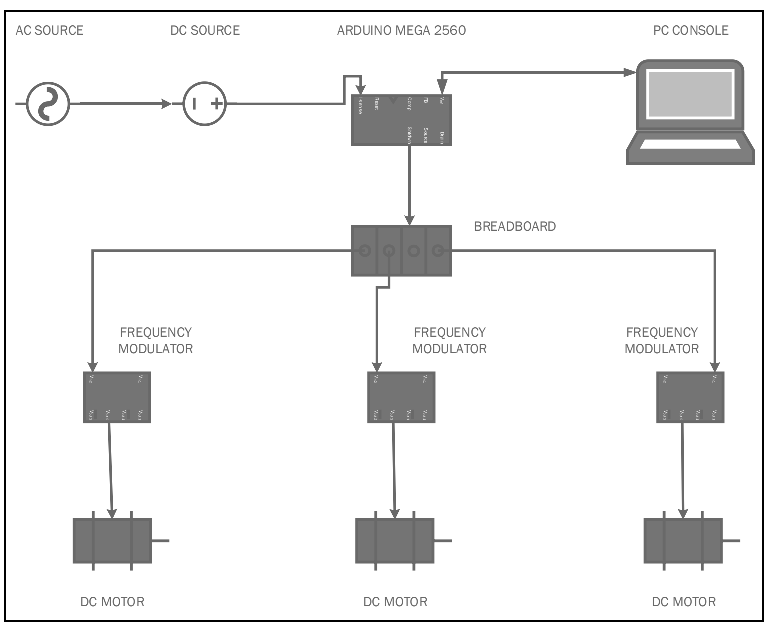

Figure 25: Control System Block Diagram

A PC is used as the control panel console which works in parallel with the power unit to control the motors. LabVIEW 2015 is used for the Graphic User Interface (GUI). LabVIEW is the graphical programming language used for the Object-Oriented Programming. As compared to the C++ or other manual programming language, it provides ease of use and integrated module for the micro-controller interfacing and GUI development.

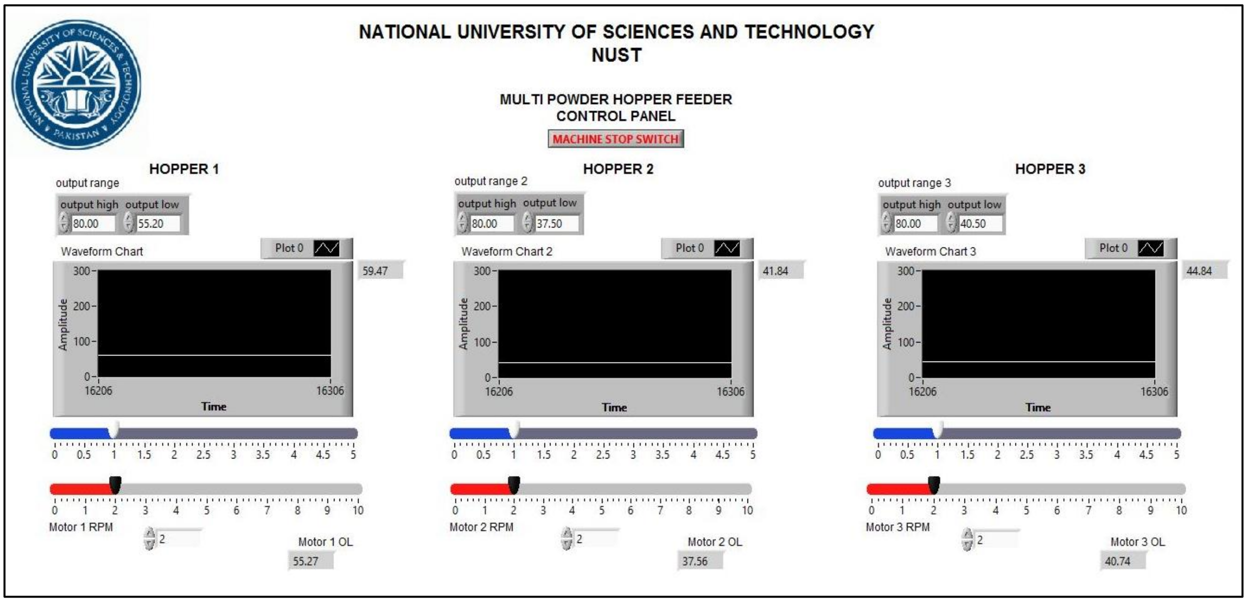

Figure 26: Graphical User Interface of the Control System in LabVIEW

Arduino Mega 2560 is the primary microcontroller in the system used for the Pulse Width Modulation (PWM) technique. Arduino, together with the LabVIEW, and Power Unit are responsible for the runtime monitoring and controlling of the Disc Motors.

To rotate the Discs at the user-defined rates, DC Servo motors were used in connection with encoders. Table 4 shows the specifications of the motors used

Table 4: Technical Specifications of Disc Motors

Description	Value
Gear Ratio	270:1
Operating Voltage	12 V
No Load Speed	40 rpm
No Load Current	250 mA
Stall Torque	80 kg-cm
Stall Current	6.5 A

Controlling the DC Motor's frequencies, Arduino alone is not satisfactory as the Arduino's output is in domain of voltage. Specific Frequency modules are used to convert the voltage signal of the Arduino to the frequency module for the motors.

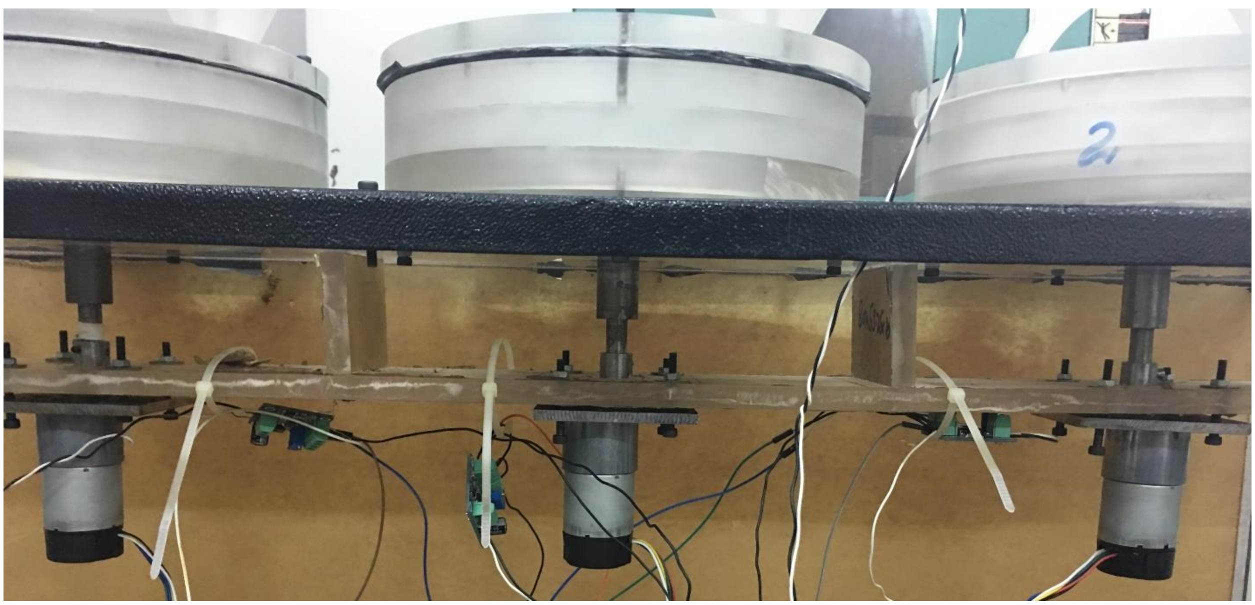

Figure 27: Control system motors mounting with the Disc shafts

The wiring diagram of the control system is attached at the end of the document as "**Appendix A**"

3.2.6 Suction Unit

Transportation of the powder from the hoppers to the destination requires the incorporation of the effective powder suction system. For the transportation of powders from the hoppers, there are very equipment currently in operation globally. For this powder hopper system, various powder transfer mechanism had been applied but the lack of efficient transportation led to variations in the powder flow rate. The tested equipment comprises of an electric pump, venturi nozzle injectors, spray gun and lastly an air operated dual diaphragm pump (AODD).

An air operated dual diaphragm pump is the type of pressure pumps which operates on the principle of the developing vacuum in the pump chamber. A compressed air source is attached to the pump to operate its diaphragms. The diaphragms move back and forth inside the pump chamber to create the pressure difference between inlet and outlet of the pump. This pressure difference drives the air from inlet to outlet and the fluid or particles travel with air through pump chamber.

Figure 28: An air operated dual diaphragm (AODD) pump

These types of pumps are in operation in various industries ranging from process industries to chemical industries. The low maintenance and operation cost added with considerable efficiency are their main attraction. Table 5 has the core specifications of the AODD pump used for the powder transportation for our developed system.

Table 5: Technical Specifications of Suction Pump

Description	Value
Pump Type	Air Operated Dual Diaphragm
Operating Source	Compressed Air
Working Pressure	0.5-8 Bar
Inlet and Outlet Line Size	0.75 inch
Body Material	Teflon

Scheduled maintenance and cleaning of the pump is essential for the optimal operation of its diaphragms. The primary concern is the availability of large amount of transferrable material for its effective operation.

3.3 Development Procedure

Following figures shows the final model of the Multi Powder Hopper Feeder. Designing phase incorporated the assembly procedures and techniques. For development procedures, the principles of DFM (Design for Manufacturing) and DFA (Design for Assembly), incorporated in the designing phase, were put up to validation.

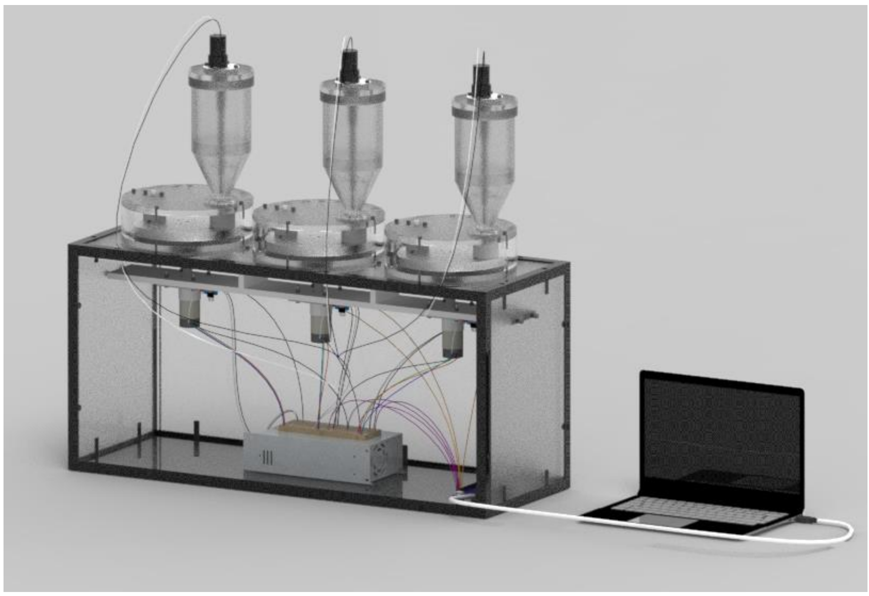

Figure 29: Isometric view of the multi powder hopper design assembly

All the components of the feeder were developed using the Computer Numerical Control (CNC) Machining techniques. Special precautions were taken for the development of Acrylic components, such as soft tools, low feed rate etc., to resist the material damage.

The development procedure included the step-by-step assembly process to overcome any shortcoming in the manufacturing of parts. Tolerance levels were variable and are proportional to the location and fitment of the individual parts. For example, parts of the disc housing, hopper parts, and concentric holes (where applicable) for the shaft and motor alignment were manufactured with tight tolerances while the basic structure sheet sizes and steel frame had the slightly flexible tolerances.

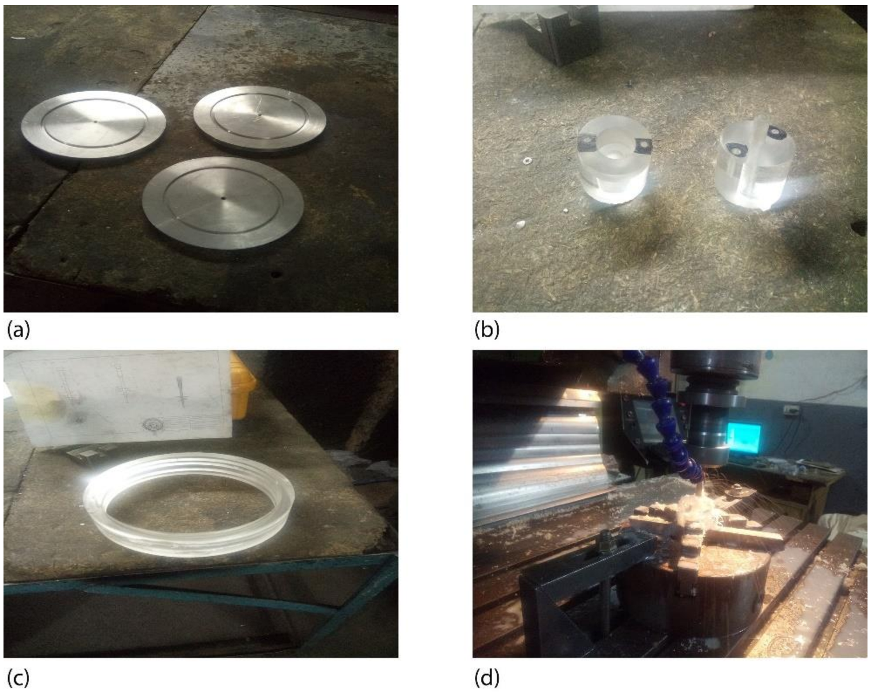

Figure 30: Manufactured parts of the powder hopper (a) powder transfer discs (b) spreader and suction tube (c) Disc housing central ring (d) CNC milling operation for the manufacturing of spreader tube

Overall, the entire development process encompassed the assembly of suction system and control system to the feeder. All the safety precautions regarding the electrical connections were conformed and the wiring was made as simple as possible. Moreover, the suction system assembly include the connection of individual venturi pump to the respective suction tube of disc housing. Mixing chamber was also connected at the outlet of the pumps to combine the individual flows for the mixing and transferring the end product as the output.

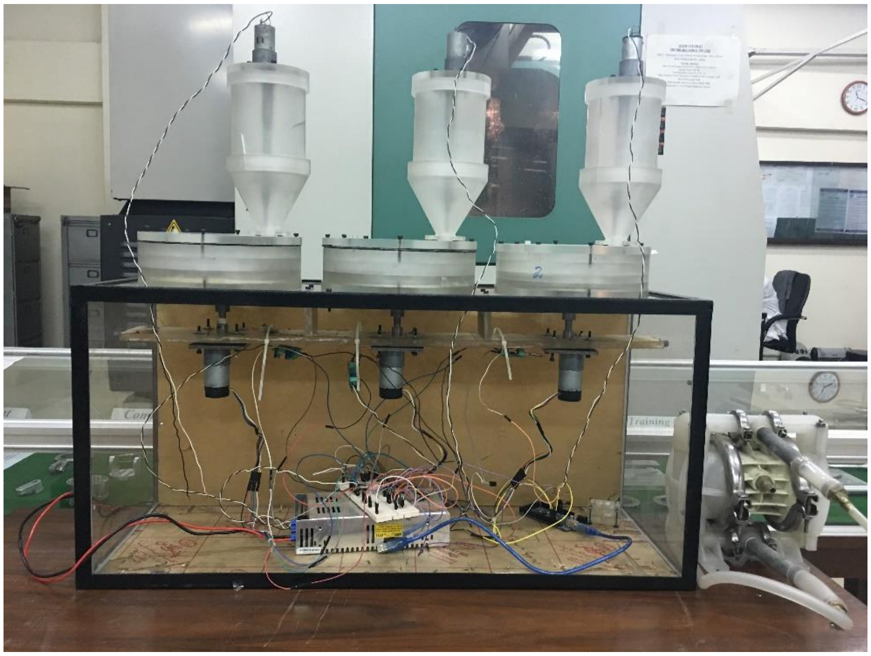

Figure 31: Multi Powder Hopper with assembled control system and suction unit

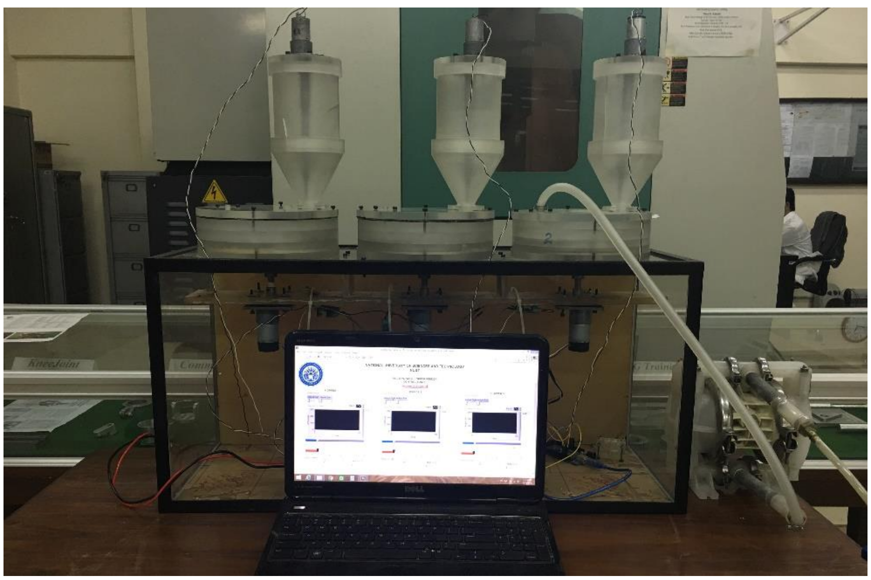

Figure 32: Operation of multi powder hopper through LabVIEW GUI

CHAPTER 4 EXPERIMENTAL PROCEDURE

This chapter include the adopted procedures for the testing of the developed feeder.

4.1 Methodology

Multi Powder Hopper will be used to transfer the powder to the laser nozzle for the laser cladding processes. The required transfer would be achieved through the efficient operation of the system by transmitting known mass of the powder for the deposition. For this matter, the experimental procedure adopted primarily concern the estimation of the mass flow rate of the powder with respect to various revolutions per minute (RPM).

As this system involves three independent modules for the powder transmission, it was essential to test the three modules independently. Each Module consists of a hopper attached to its respective suction and spreader tube and powder transmission disc. The methodology adopted include calculations of the mass flow rate of the test powder at various revolutions per minute. The conformity of the results of all three module with one another is crucial for the successfulness of the experimental procedures owing to the fact that all three modules are dimensionally symmetric.

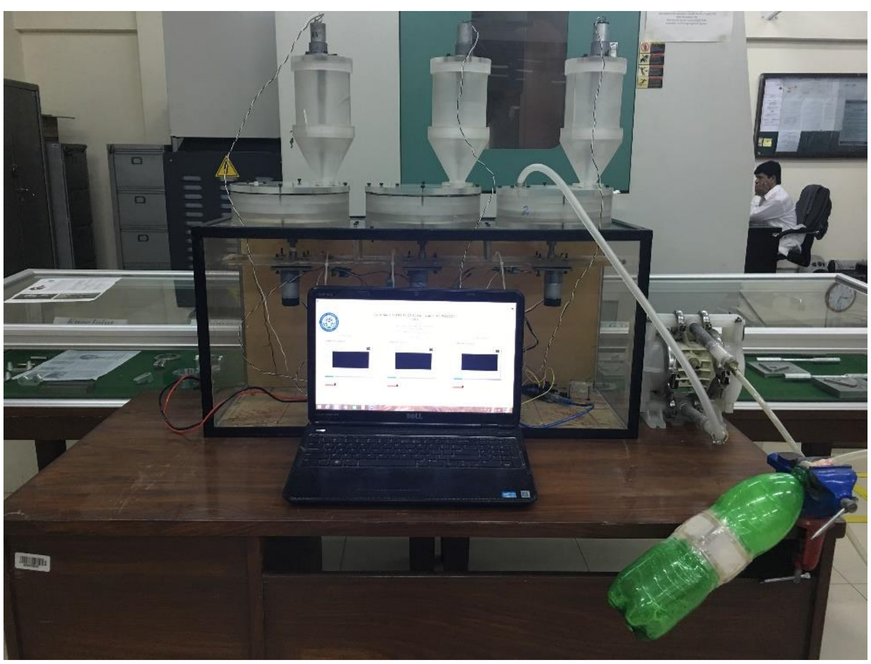

Figure 33: Experimental Setup for the determination of mass flow rate of the modules

4.2 Test Powder Specification

For the experimental procedure, the test powder used was the Silica Sand. (details of the Silica Sand). The primary objective for the usage of sand instead of metallic powder is to ensure personal as well as work safety due to sensitivity of using metallic powder. Moreover, the initial testing of the system may have invariable results and that could be catered by using sand instead of metallic powder.

Table 6: Test Powder Specifications

Description	Value
Material	Silica Sand
Mesh Grade	100
Particle Size Range	50 µm to 120 µm

4.3 Experimentation

The experimental process involves the testing of individual module at four different values i.e. 2,4,6, and 8. At each RPM, three runs were done to check the repeatability of the hoppers. The focused parameter for the determination of mass flow rate is gram per second

To determine the mass flow rate of the powder is not straight forward. Due to its physical properties, powders accurate mass determination is somewhat difficult to calculate. The mass of the powder mostly dependent upon the specification of the container in which it is placed. For this matter, the parameter of Bulk Density is introduced. Bulk Density is the ratio of mass of the powder in the container to the volume of the container.

$$Bulk\ Density = \frac{Mass\ of\ the\ powder\ in\ the\ container}{Volume\ of\ the\ container}$$

However, the mass of the powder in the container couldn't be the absolute value because of large amount of air gaps in the powder particles. To overcome this factor, an average of different measurements of mass is taken and divide that with the volume of the container to obtain the bulk density of the powder in the container. Table 7 contain the major dimensions of the container used for the calculation of powder mass.

Table 7: Specifications of the Container

Description	Value
Diameter	9 cm
Total Height	11.8 cm
Volume	750.303 cm^3

All three hoppers were examined for the calculation of mass flow rate at above mentioned revolutions per minute. Following sections will have the experiments data sectioned into three hoppers and all the test sheets of the experimentations are attached at the end of the document as "**Appendix B**".

4.3.1 Experimentation Results of Module 1

As stated above, three samples of the powder flow were collected at every rpm. This constitute to total of 12 experiments of each module.

4.3.1.1 Sample 1

Sample 1 include the first set of experiments performed at module 1 at rpms of 2, 4, 6 and 8. As mentioned above, Test number from 1 to 4 in Appendix B have all the data of the sample 1. However, Table 8 contains the major specifications of the first sample extracted from module 1.

Table 8: Module 1 results from the Sample 1

Revolution per Minute (RPM)	Mass Flow Rate (gram per second)	Mass Flow Rate (gram per minute)
2	0.138	8.267
4	0.276	16.559
6	0.514	30.847
8	0.803	48.181

Figure 34 shows the graphical representation of the data mentioned in the Table 7

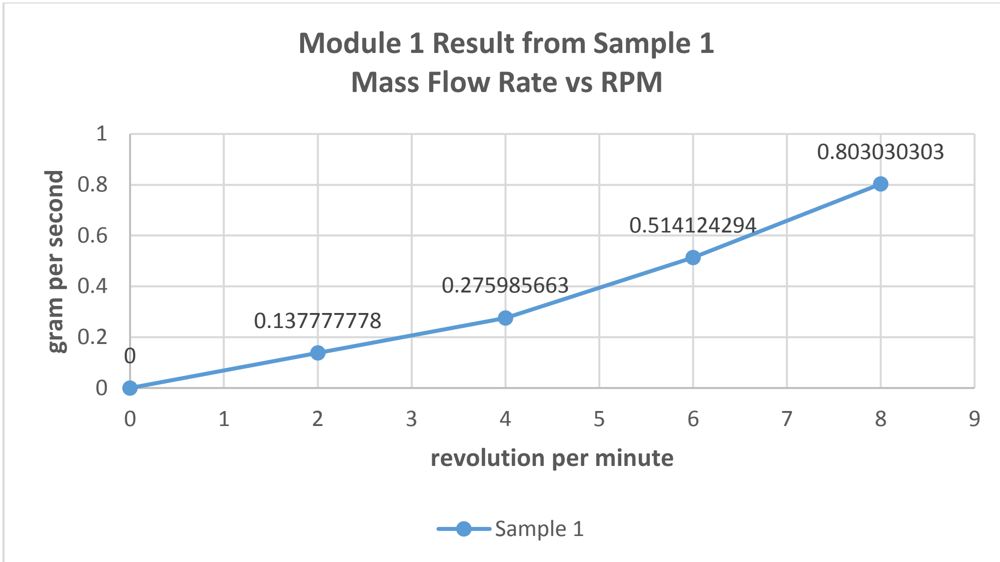

Figure 34: Graphical results of Module 1 at Sample 1

4.3.1.2 Sample 2

Sample 2 is the second set of experiments performed at module 1. Table 9 have the mass flow rates calculated at same four rpms.

Table 9: Module 1 results from Sample 2

Revolution per Minute (RPM)	Mass Flow Rate (gram per second)	Mass Flow Rate (gram per minute)
2	0.147	8.8
4	0.260	15.609
6	0.532	31.929
8	0.754	45.263

Figure 35 is the graphical representation of Table 8

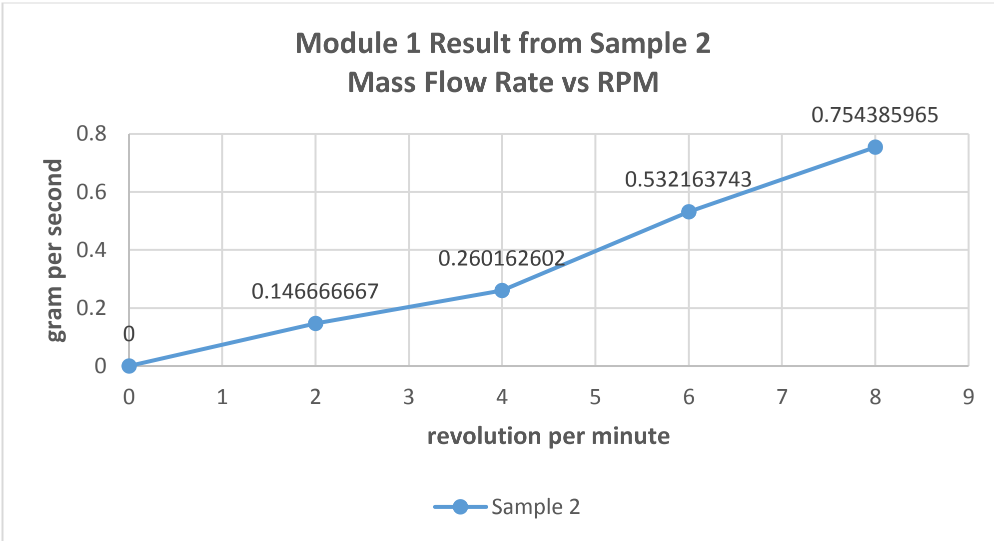

Figure 35: Graphical results of Module 1 at Sample 2

Detailed information regarding this sample test is included in test sheets from 5 to 8 in Appendix B.

4.3.1.3 Sample 3

Sample 3 have the data of third set of experiments at module 1. Table 10 shows the data collected for the mass flow rates against the respective rpm.

Table 10: Module 1 results of Sample 3

Revolution per Minute (RPM)	Mass Flow Rate (gram per second)	Mass Flow Rate (gram per minute)
2	0.150	9.01
4	0.271	16.285
6	0.563	33.818
8	0.828	49.714

Figure 36 shows the chart developed upon the data in Table 9.

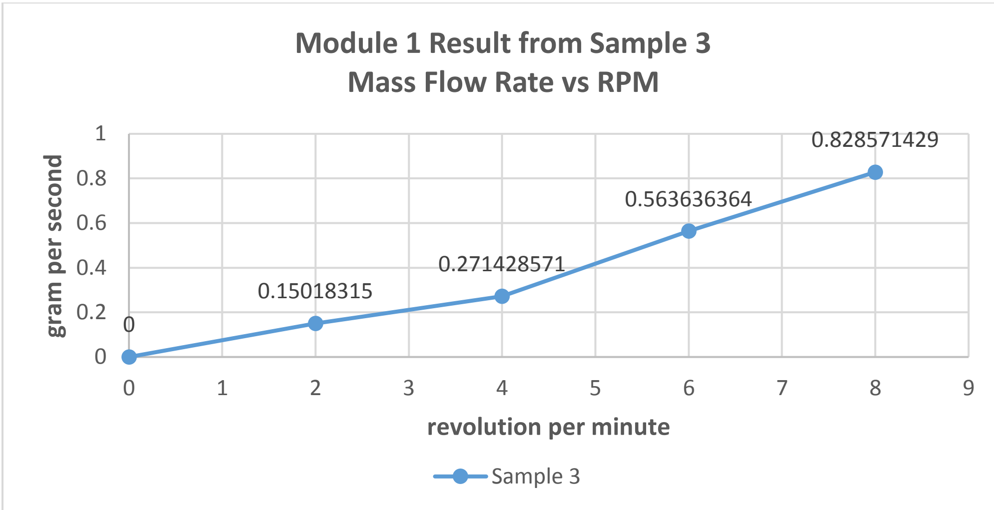

Figure 36: Graphical results of Module 1 at Sample 3

Detailed information regarding this sample is present in test number 9 to 12 in Appendix B.

4.3.2 Experimentation Results of Module 2

This section covers the results collected from 12 experiments performed at Module 2. The methodology of the experiments was similar to the discussed of Module 1. Following sections have the data collected from three samples of experiments of Module 2.

4.3.2.1 Sample 1

Table 11 has the results of Sample 1 results with figure 37 illustrating the results

Table 11: Module 2 results of Sample 2

Revolution per Minute (RPM)	Mass Flow Rate (gram per second)	Mass Flow Rate (gram per minute)
2	0.136	8.372
4	0.279	16.740
6	0.609	36.585
8	0.819	49.189

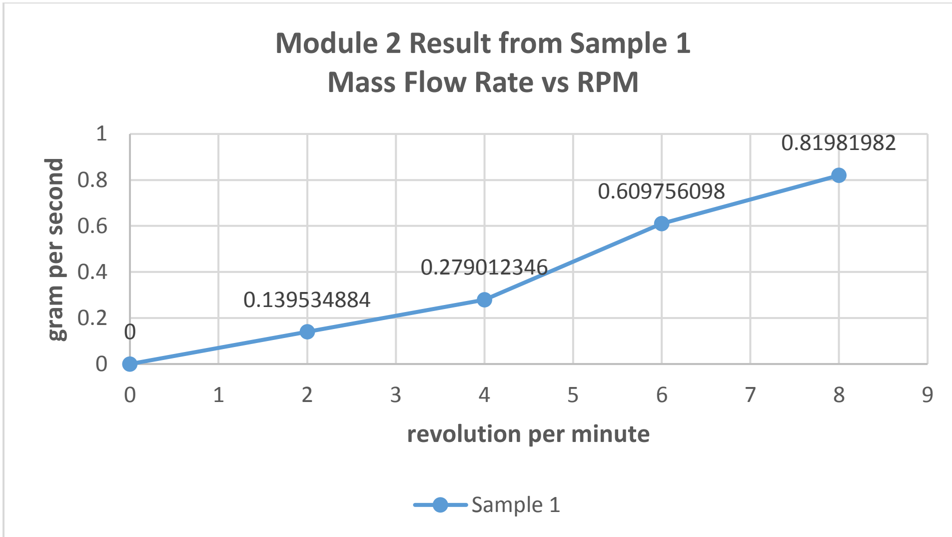

Figure 37: Graphical results of Module 2 at Sample 1

Detailed information regarding this sample data is present in test numbers 25 to 28 in Appendix B.

4.3.2.2 Sample 2

Table 12 contain the results of experiments conducted in Sample 2 of Module 2

Table 12: Module 2 results of Sample 2

Revolution per Minute (RPM)	Mass Flow Rate (gram per second)	Mass Flow Rate (gram per minute)
2	0.125	7.520
4	0.255	15.333
6	0.538	32.307
8	0.731	43.913

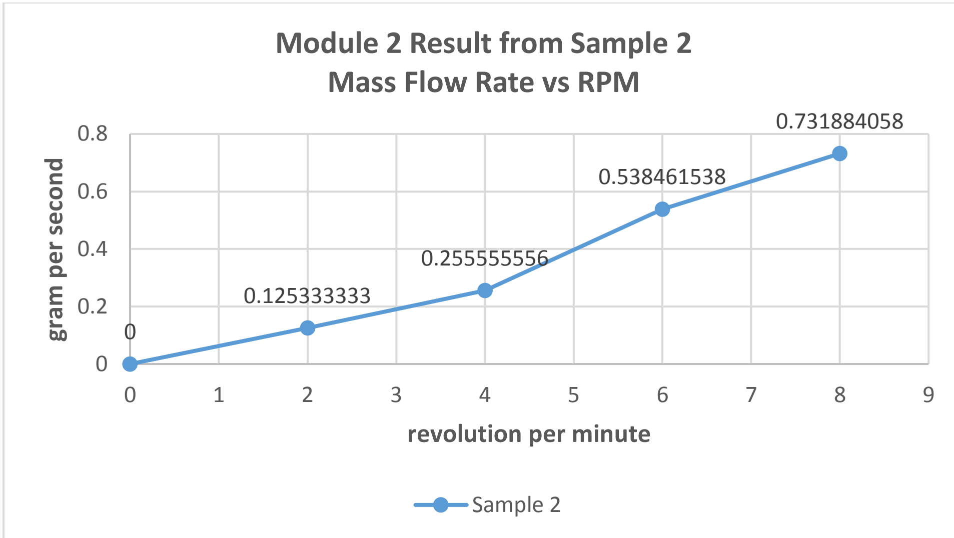

Figure 38: Graphical results of Module 2 at Sample 2

In Appendix B, test numbers 29 to 32 have the detailed information regarding the test specifications and input parameters of this sample.

4.3.2.3 Sample 3

Table 13 presents the mass flow rate values respective to the selected revolutions per minute.

Table 13: Module 2 results of Sample 3

Revolution per Minute (RPM)	**Mass Flow Rate (gram per second)**	**Mass Flow Rate (gram per minute)**
2	0.132	7.937
4	0.243	14.615
6	0.483	29.032
8	0.747	44.827

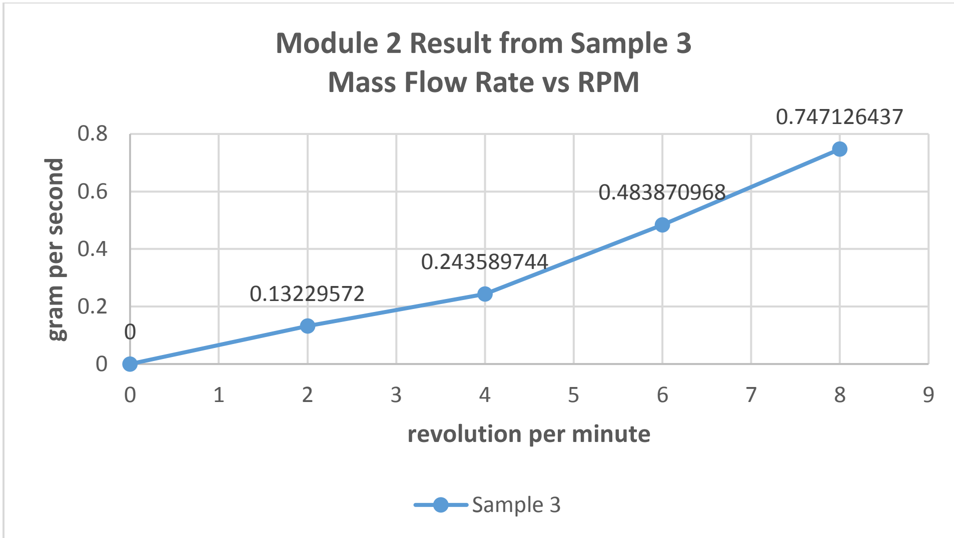

Figure 39: Graphical results of Module 2 at Sample 3

Detailed information of the data of the Sample 3 are mentioned in test numbers 33 to 36 in Appendix B.

4.3.3 Experimentation Results of Module 3

As similar, this section has the results of the experiments run at Module 3 of the powder feeder. All the subsections constitute the data of the mass flow rates determined by three samples at selected revolutions

4.3.3.1 Sample 1

Table 14 shows the mass flow rates achieved at the selected revolutions.

Table 14: Module 3 results of Sample 1

Revolution per Minute (RPM)	Mass Flow Rate (gram per second)	Mass Flow Rate (gram per minute)
2	0.134	8.076
4	0.201	12.075
6	0.604	36.296
8	0.744	44.666

Figure 40 has the graphical demonstration of the values obtained and mentioned in Table 13

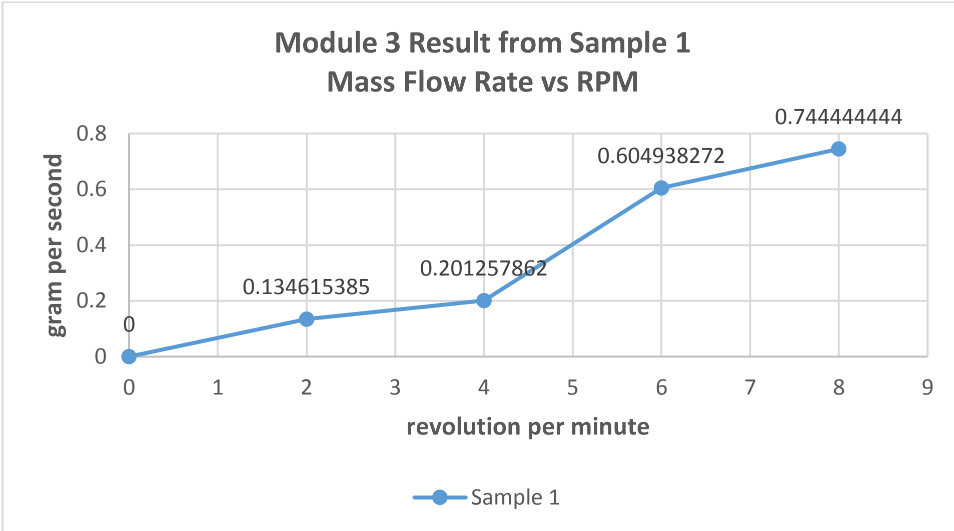

Figure 40: Graphical results of Module 3 at Sample 1

In Appendix B, test numbers 13 to 16 have the complete information of the test performed for this sample.

4.3.3.2 Sample 2

The values obtained during this sample run are mentioned in the Table 15.

Table 15: Module 3 results of Sample 2

Revolution per Minute (RPM)	Mass Flow Rate (gram per second)	Mass Flow Rate (gram per minute)
2	0.137	8.235
4	0.273	16.428
6	0.583	35.0
8	0.676	40.571

Following figure 41 depicts the behavior of the module in this sample test.

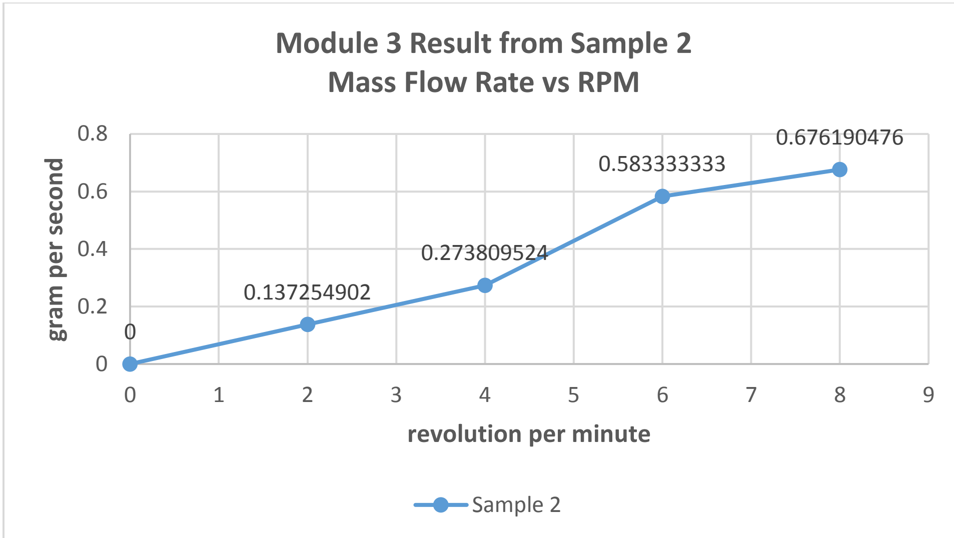

Figure 41: Graphical results of Module 3 at Sample 2

Test numbers 17 to 20 in the Appendix B have the information regarding the input the output parameters

4.3.3.3 Sample 3

Table 16 shows the values of powder mass flow rates obtained in this sample test at respective revolutions.

Table 16: Module 3 results of Sample 3

Revolution per Minute (RPM)	Mass Flow Rate (gram per second)	Mass Flow Rate (gram per minute)
2	0.140	8.40
4	0.308	18.50
6	0.556	33.334
8	0.823	49.411

Following figure 42 presents the graphical behavior of the feeder module during this sample test.

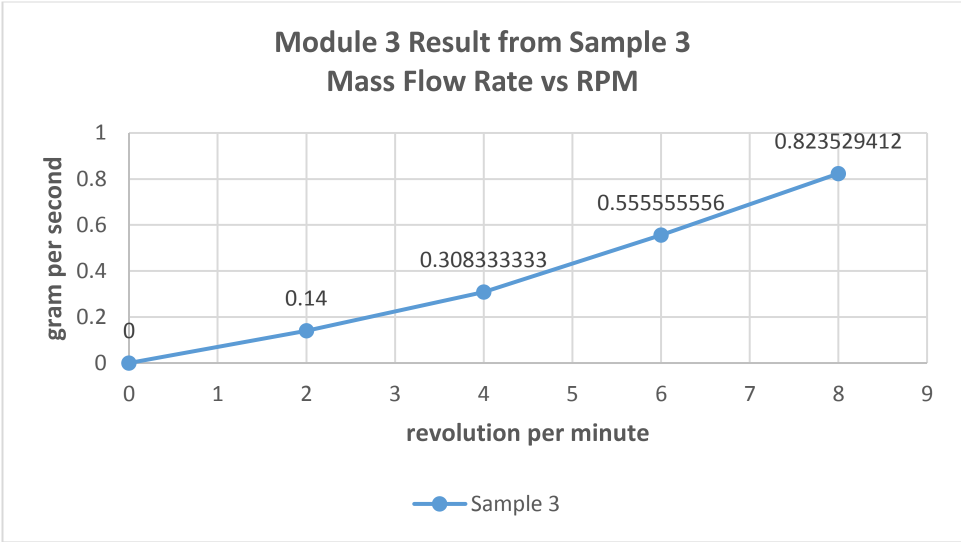

Figure 42: Graphical results of Module 3 at Sample 3

Test numbers 21 to 24 of the Appendix B have the entire data of the values and data calculated and measured for this sample. Discussions and conclusions of the results obtained by performing all the tests on three modules are discussed in the subsequent chapter.

CHAPTER 5 RESULTS AND CONCLUSIONS

This chapter reflect upon the test data and values obtained by performing tests upon the powder feeder for the determination of the operation worthiness of the feeder. The discussions upon the results pave way for the final conclusions and remarks adding the future recommendation for the design and operation optimization of the powder feeder.

5.1 Results Discussion

Graphical demonstration in figures 43,44 and 45 shows the trend of the all three samples of module 1, 2 and module 3 respectively.

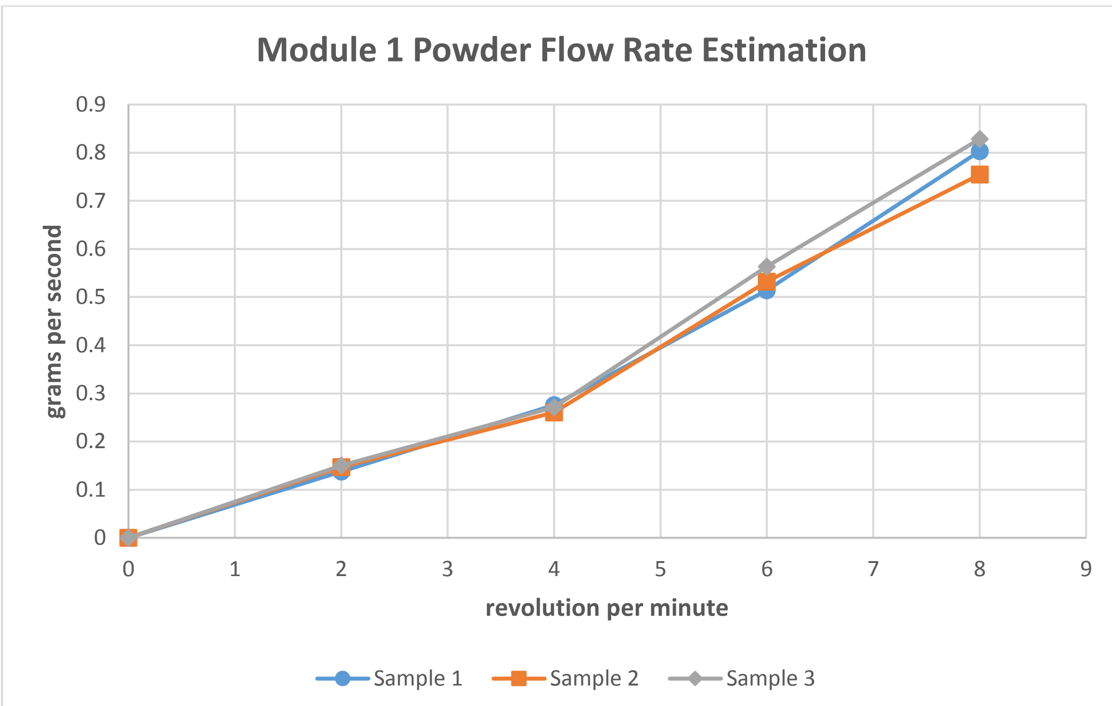

Figure 43: Combined results of three sample test of Module 1

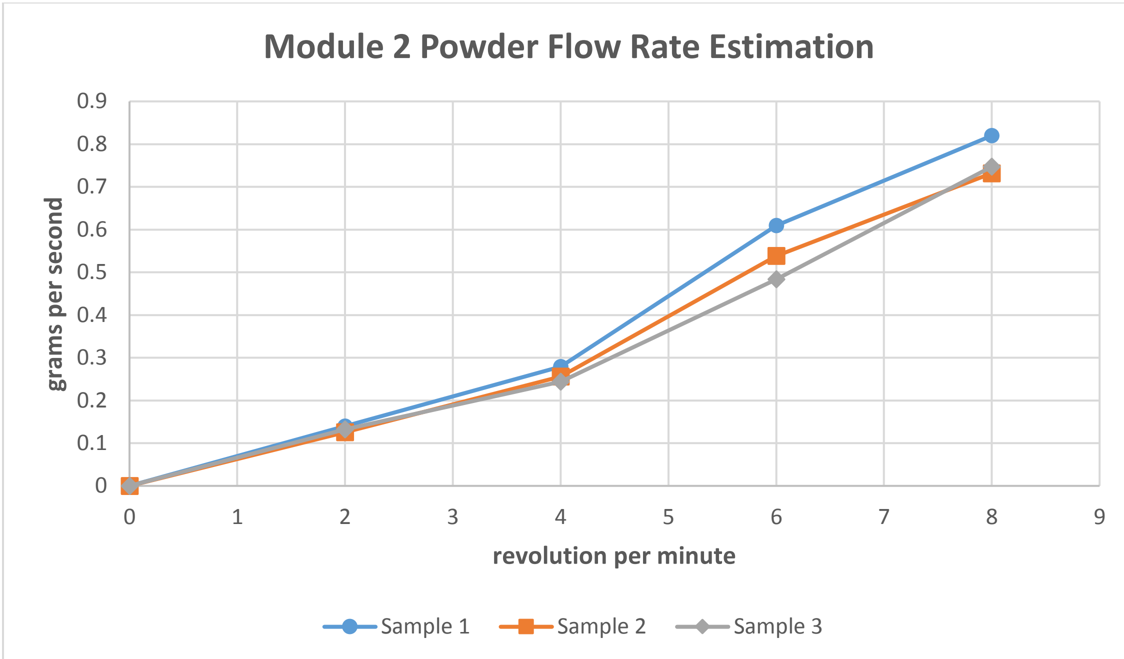

Figure 44: Combined results of three sample test of Module 2

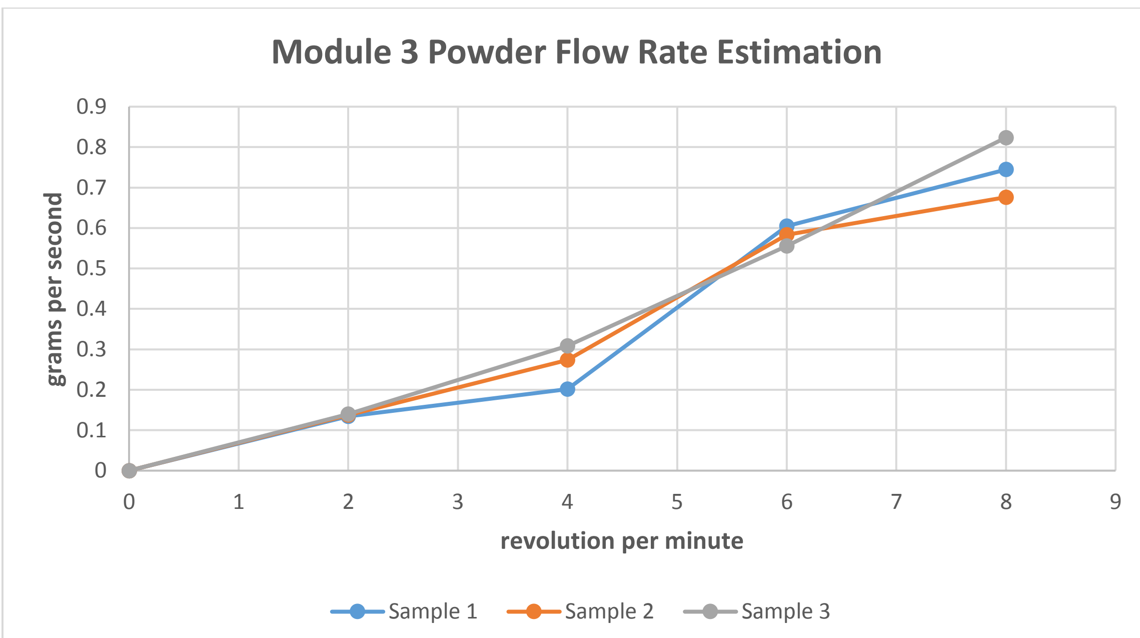

Figure 45: Combined results of three sample test of Module 3

The behavior depicted in the figure shows that the results of the samples at the same rpm has a close relation with one another. The trend of the results shown in the above graphics shows that the system produces a repeatable trend in the results. At the top of the trend in the figure, there is a difference in the mass flow rates of the test powder. This is due to the fact that there is no renowned economical process or equipment available for the separation of air-powder mixture. The equipment used for the air separation is based upon the centrifugal process and the equipment used are not economical. The approach used to collect the transferred powder at the outlet was not very efficient and that results in variable results at the high rpms. Moreover, the objective of the developed multi powder hopper is to transfer powder direct to the coaxial laser beam nozzle.

This experimentation of the powder hopper is to determine the repeatability of the developed powder hopper. At slow revolutions, the difference in the results were not too much. As the trends presented in the figures 44 and 45, the trend shown in the figures are same as in figure 43. The trend shown in all three figures has predicted the repeatable behavior of the system. Furthermore, the operation of the system was seemed to be repeating the same behavior in all modules and at selected revolutions per minute.

5.2 Conclusions

From the results mentioned in Chapter 4, test sheets attached in Appendix B and the discussions presented in the Chapter 5, the developed multi powder hopper modules predicted symmetric and repeatable behavior under different revolutions per minute and under various tests and examinations. The calculated results showed that the multi powder hopper is suitable for use in the laser cladding process. Furthermore, the developed system is also capable of operating satisfactory in processes related to powder transfer, powder collection and powder mixing.

One of the primary goals of the research to develop an economical powder feeder and mixer for the local industries of Pakistan. Keeping in view this way, the development and design expenditure of this system is economical as compared to the commercial available equipment and systems. Moreover, the flowability of powder through the hopper and the suction tubes was satisfactory smooth.

As far as the design of the multi powder hopper is concerned, the core principles of Design for Manufacturing (DFM) and Design for Assembly (DFA) were followed and the design of the system is made as much modular as possible for its efficient maintenance, operation and part replacement processes. This design will benefit the future optimization in same base structure.

5.3 Future Recommendations

Efforts were made to design the multi powder hopper to suit majority of operating conditions and situations. However, there is always place for improvement and optimization in the design, manufacturing and experimentation setup. Following areas can be opted for the optimization of the system in future

a. New and improved design of the suction and spreader tubes for more efficient powder transport and assembly.
b. Improved powder collection mechanism to determine improved data. However, this mechanism doesn't contribute towards standard operation of the powder hopper.
c. Geared motor assembly for the control system of the device.
d. New and improved electronics and electrical connections and assembly for more modular approach
e. Extension of the system to more than three hoppers to develop more and more economical process solutions for the local and global industry
f. More efficient approach towards powder transfer mechanism to transfer optimum amount of the powder with less energy consumption
g. Console development of the system to house all the associated parts and equipment. This will contribute towards portability and expanded scope of the operation.

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