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Design and Fabrication of a Bench Top Pellet Filament Extruder System for 3-D Printing Applications

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ABSTRACT

The project aims to develop an innovative and compact system capable of producing high-quality 3D printing filaments from plastic pellets. The system incorporates crucial components, including a shredder for efficient material processing, speed control for precise filament production, a temperature controller for optimal extrusion conditions, and a spooling mechanism for convenient handling. Additionally, the system integrates a recycling feature to repurpose discarded prints and unused filaments, contributing to sustainability in the additive manufacturing industry. The project involves various stages such as system design, component selection, fabrication, testing, and performance evaluation, with a focus on enhancing filament production efficiency and promoting recycling practices. The successful implementation of this comprehensive system will advance the production and recycling capabilities of 3D printing filaments, paving the way for more sustainable and cost-effective additive manufacturing processes.

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LIST OF SYMBOLS

Latin Letters

V	Velocity
M	Mass
F	Force
Q	Volumetric Flow Rate
P	Pressure

Greek Letters

$\boldsymbol{\theta}$	Primary Angle
ϕ	Secondary Angle
η	Viscossity
Δ	Rate of change
π	Pi
γ	Shear Rate

Chapter 1

Introduction

1.1 Background

Thermoplastic materials, such as PLA (Polylactic Acid), ABS (Acrylonitrile Butadiene Styrene), TPU (Thermoplastic Polyurethane), and others, have gained significant popularity in the field of 3D printing due to their unique properties and versatility. These materials offer a wide range of characteristics, making them suitable for various applications in additive manufacturing.

PLA, derived from renewable resources, is biodegradable and environmentally friendly. It has low printing temperatures, minimal warping, and excellent surface finish, making it ideal for prototyping and aesthetic models. ABS is known for its strength, durability, and higher temperature resistance compared to PLA. It is commonly used for functional prototypes and parts requiring impact resistance. TPU, on the other hand, is a flexible and elastic thermoplastic used for producing rubber-like and flexible components.

The significance of recycling thermoplastic materials on a large scale lies in promoting sustainability in the 3D printing industry. As 3D printing continues to grow, the demand for filament production increases, leading to a corresponding rise in plastic waste. Recycling these thermoplastics can help address this issue by reducing environmental impact and conserving resources.

Large-scale recycling of thermoplastics enables the recovery and reutilization of discarded prints, failed prints, and unused filaments. It minimizes the need for virgin plastic production, conserving energy and reducing greenhouse gas emissions associated with the manufacturing process. Recycling also provides a cost-effective approach, as recycled materials can be used for filament production at a lower cost compared to new materials.

Furthermore, recycling thermoplastic materials promotes circular economy principles, where waste is seen as a valuable resource. By closing the loop and recycling plastics, the industry can contribute to a more sustainable and environmentally conscious approach to additive manufacturing.

However, recycling thermoplastics for 3D printing filament production does come with challenges. It requires proper sorting, cleaning, and processing techniques to ensure the quality and performance of the recycled material. Additionally, efforts are needed to develop standardized recycling processes and improve awareness and infrastructure for recycling in the 3D printing community.

PLA (Polylactic Acid) stands out as the preferred filament for 3D printing due to its unique properties and eco-friendly nature. This thermoplastic material is derived from lactic acid, a monomer obtained through the fermentation of renewable resources like corn, sugarcane, and potatoes. The synthesis of high-molecular-weight PLA involves various methods, including direct condensation polymerization, azeotropic dehydrative condensation, and ring-opening polymerization of lactide.

The exceptional biocompatibility and biodegradability of PLA have contributed to its popularity. Its thermoplastic nature enables convenient processing using standard polymer-processing equipment and techniques. PLA can be transformed into various forms such as fiber, film, sheet, and 3D articles through techniques like fiber drawing, film blowing, extrusion, and injection molding.

One notable characteristic of PLA is its clarity, making it an excellent choice for biodegradable packaging applications such as bottles, food containers, and wrappers. It has found utility in diverse fields including food service ware, lawn and food waste bags, coatings for paper and cardboard, as well as fibers for clothing, carpets, sheets, towels, and wall coverings.

In the realm of biomedical applications, PLA has made significant strides. It is utilized in sutures, stents, prosthetic materials, dialysis media, and drug delivery devices, leveraging its biocompatibility and tailored degradation properties.

Speaking of degradation, PLA undergoes primarily hydrolysis in a two-stage process, gradually breaking down over time in an environmentally friendly manner.

Overall, PLA's versatility, biodegradability, and compatibility with existing processing methods have positioned it as the material of choice for a wide range of applications, showcasing its potential for sustainable manufacturing and reducing environmental impact [1].

In conclusion, the large-scale recycling of thermoplastic materials used in 3D printing has significant environmental and economic benefits. It promotes sustainability, reduces waste, conserves resources, and supports the transition towards a circular economy model within the additive manufacturing industry.

1.2 Problem Statement

The proliferation and utilization of thermoplastic polymers, including popular variants such as PLA, ABS, PETG, TPU, PEEK, and others, have raised significant concerns regarding their impact on human health, ecosystems, high manufacturing costs, and limitations in recycling. These multifaceted challenges necessitate urgent attention and action to mitigate the environmental and health risks associated with these materials.

Firstly, thermoplastic polymers have been linked to adverse effects on human health. Many of these polymers release potentially harmful chemicals during manufacturing, use, and disposal. These chemicals, such as phthalates, bisphenol A (BPA), and flame retardants, have been associated with endocrine disruption, reproductive disorders, developmental issues, and potential carcinogenic effects. Continuous exposure to these chemicals through inhalation, ingestion, or skin contact poses risks to individuals, requiring immediate attention for safeguarding public health.

Secondly, the environmental impact of thermoplastic polymers extends to ecosystems. Improper disposal, limited recycling options, and their non-biodegradable nature result in the accumulation of plastic waste in landfills, water bodies, and natural habitats. This accumulation contributes to environmental degradation, habitat destruction, and harm to marine and terrestrial life. Microplastics, derived from the breakdown of thermoplastic polymers, further exacerbate the problem, infiltrating the food chain and posing risks to various species and ecological systems.

Furthermore, the high manufacturing costs associated with thermoplastic polymers present economic and environmental challenges. The production processes for these polymers often rely on fossil fuels and energy-intensive procedures, leading to increased carbon emissions, resource depletion, and higher costs. These factors not only impede their widespread adoption but also limit the affordability of sustainable alternatives. For instance, PLA has a manufacturing cost of $25 per kg which makes it a very expensive polymer. Furthermore, an amount of filament is wasted during 3D printing because of failed prints or rejected support structures. In early 2019, a survey was conducted by Filamentive which showed that about 6-19 % of the filament is wasted during each 3D printing operation [2]. According to a comprehensive report on the US 3D Printing Filament Market in 2022, it was revealed that a staggering 2.2 million 3D printers were installed across the United States. Furthermore, on average, each 3D printer operator consumed approximately 12 kilograms of filament per year. This information allows us to estimate the amount of waste plastic generated by US 3D printing users in 2022, which amounts to a substantial 3.3 million kilograms [2].

These numbers highlight the significant volume of waste generated by the 3D printing industry. It underscores the importance of sustainable practices and the need for environmentally friendly alternatives, such as biodegradable filaments like PLA, which can help reduce the environmental impact associated with traditional plastic waste.

Additionally, the limitations in recycling thermoplastic polymers further compound their environmental impact. The diverse range of thermoplastics available, each with different properties and composition, makes it challenging to establish efficient and cost-effective recycling processes. Inadequate recycling infrastructure and lack of standardized practices contribute to a significant proportion of thermoplastic waste ending up in landfills or incineration, exacerbating environmental pollution and resource depletion.

Addressing the multifaceted challenges posed by thermoplastic polymers in terms of their impact on health, ecosystems, high manufacturing costs, and recycling limitations is essential for sustainable development. Developing safer alternatives, implementing efficient recycling technologies, promoting circular economy models, and fostering awareness about the environmental and health consequences of thermoplastic polymers are critical steps toward mitigating their negative effects on human well-being and the ecosystem.

1.3 Objectives

Based on the previous discussion, it is essential to conduct research and envision a design for a Filament Recycler that encompasses the following key features:

- Conversion of wasted filament material into pellets.
- Mixing of wasted 3D prints, additives, and virgin filament pellets during the recycling process to create custom filaments.
- Production of a filament strand with the desired shape and size.

- Precise temperature control in the feeding, melting, and metering regions.
- Diameter measurement of the produced filament for feedback purposes.
- Creation of a recycled filament strand with chemical and structural properties closely resembling those of new filament.

With these objectives in mind, the anticipated outcomes of this project are as follows:

- Manufacture the filament recycler with cost efficiency in mind.
- Design the recycler to minimize the use of fresh material.
- Optimize the design to minimize the time required for material melting.
- Incorporate a microcontroller to control key features such as motor speed, band heaters temperature, diameter gauge, and spooling speed.
- Develop the recycler design to cater to both industrial and research needs.
- Ensure ease of operation in the design.
- Implement adequate safety features within the design.

1.4 Sustainable Development Goals

Goal 9 (Industry, Innovation, and Infrastructure): To achieve the goals of building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation. The basic purpose in the development of this filament recycler is to work on the design of a relatively newly envisioned machine. Here's how it aligns with SDG #9:

Improving Industrial Processes: The project involves designing and fabricating a benchtop pellet filament extruder system. This contributes to SDG #9 by promoting sustainable industrial processes and enhancing manufacturing capabilities. The system enables the production of 3D printing filaments using recycled materials, which reduces the dependency on virgin plastic and contributes to a more sustainable production method.

Enhancing Manufacturing Efficiency: The inclusion of features like shredder, speed control, and temperature controller in the extruder system improves manufacturing efficiency. By optimizing the extrusion process, it reduces waste and increases the yield of high-quality 3D printing filaments. This aligns with SDG #9, which emphasizes the need for sustainable and efficient industrial production.

Advancing Technology and Innovation: The FYP involves the development of a benchtop pellet filament extruder system, incorporating various technological components and mechanisms. This project fosters innovation by creating a novel solution for producing and recycling 3D printing filaments. By advancing technology in this field, the project contributes to SDG #9, which encourages technological advancements and innovation in industry.

Resource Efficiency and Waste Reduction: The incorporation of a shredder in the extruder system enables the recycling of plastic waste. This promotes resource efficiency and waste reduction by converting plastic waste into valuable 3D printing filaments. By reducing the consumption of new plastic materials and diverting waste from landfills, the project aligns with SDG #9's aim to promote sustainable consumption and production.

Accessibility and Affordability: The production of 3D printing filaments using recycled materials contributes to making 3D printing more accessible and affordable. By utilizing recycled plastic pellets, the cost of filament production is reduced, making it more affordable for users. This aligns with SDG #9's objective of making technology more accessible and affordable to all.

A filament recycler proposes a whole new aspect of recycling plastic materials. This filament recycler recycles the wasted filament material by blending it with some quantity of fresh filament material. The use of blending is an innovation in the field of plastic recycling. As 3D printing is considered the backbone of industrial modernization, this filament recycler promotes the use of 3D printing machines in the new industrial era by reducing the high costs and environmental hazards associated with 3D printing. To withstand high temperatures, pressures, and forces required for extrusion mechanism, the filament recycler demands a resilient body and infrastructure. Therefore, we have chosen goal 9 of SDGs to be our main target as it promotes resilience of infrastructure and the idea of innovation.

Furthermore, as mentioned above, the research in this aspect is very little or unpublished. This leads us to the idea of a new design envisaged and implemented without any prior development. For this purpose, due research, analysis, trials, improvements, and development is needed. This fosters the idea of innovation in the sense that the machine is indigenously developed. Hence, UN SDG number 9 fits the demand of our design.

Goal 3 (Health and Well-Being):

To ensure healthy lives and promote well-being for all at all ages. To work for the betterment of health and environment of our ecosystem is also a main purpose of the filament recycler.

In early 2019, a survey was conducted by Filamentive which showed that about 6-19

% of the filament is wasted during each 3D printing operation. Irrespective of the filament type used in 3D printing, it is important to be aware of the potential emission of ultrafine particles or nanoparticles. These particles, although invisible to the human eye, can pose health risks. Due to their small size, ultrafine particles can be absorbed by the cells lining the lungs, and unlike larger particles, they have the ability to diffuse through the initial lining and reach deeper organs, including the brain.

The inhalation of ultrafine particles has been linked to various health issues. These particles can cause inflammation in the lungs, leading to conditions such as bronchitis and asthma. Additionally, there is a potential impact on the cardiovascular system. Furthermore, scientists have observed a correlation suggesting that the inhalation of ultrafine particles may have carcinogenic properties, potentially increasing the risk of cancer.

It is crucial to take appropriate precautions when working with 3D printers and filaments to minimize exposure to these particles. This can include implementing proper ventilation systems, using personal protective equipment such as masks or respirators, and working in well-ventilated areas. It is also important to stay informed about the latest research and guidelines regarding the safe use of 3D printing technology to ensure the well-being of individuals involved in the process [3]. Thus, to ensure a healthy and safe environment for people of all ages, we need to protect our ecosystem from all the harms of 3D printing discussed above. And to achieve this objective, recycling of 3D printing filament is the cleanest approach to solve the ever-increasing issue of plastic pollution.

Hence, UN SDG number 3 also fits the demand of our design.

Goal 13 (Climate Change):

This project can contribute to promoting Sustainable Development Goal (SDG) #13, which focuses on climate action. Here's how it aligns with SDG #13:

1. Climate Change Mitigation: The project promotes climate change mitigation by addressing two key aspects: reducing greenhouse gas emissions and conserving resources. By recycling 3D printing filaments, the project reduces the need to produce new filaments from virgin materials, which typically have a higher carbon footprint By incorporating the use of recycled filaments, the project aims to contribute to the reduction of greenhouse gas emissions that are typically associated with the production process.
2. Resource Efficiency and Waste Reduction: The inclusion of a shredder in the system enables the recycling of post-consumer or post-industrial waste plastic materials, such as failed 3D prints or plastic objects, into usable filaments. This process reduces waste,

promotes circular economy principles, and minimizes the consumption of new resources, thus supporting resource efficiency.

3. Energy Efficiency: The incorporation of a speed control mechanism and temperature controller helps optimize the energy efficiency of the filament extruder system. By controlling the speed and temperature, the system can operate at the most energy-efficient levels required for the extrusion process. This feature reduces energy consumption and contributes to mitigating climate change by reducing the carbon footprint associated with energy production.
4. Technology Innovation: The development of a benchtop pellet filament extruder system with various functionalities demonstrates technological innovation for sustainable production and recycling of 3D printing filaments. By improving the efficiency and accessibility of filament recycling, the project encourages the adoption of sustainable practices in the 3D printing industry.
5. Knowledge Sharing: The completion of this FYP allows for the dissemination of knowledge and expertise in the field of sustainable 3D printing filament production and recycling. Sharing the project findings, methodologies, and designs can inspire and inform others, fostering a broader adoption of sustainable practices in the 3D printing industry and contributing to SDG #13.

Overall, by designing and fabricating a benchtop pellet filament extruder system that incorporates shredding, speed control, temperature control, and spooling mechanisms, your FYP promotes SDG #13 (climate action) through climate change mitigation, resource efficiency, waste reduction, energy efficiency, technology innovation, and knowledge sharing in the context of 3D printing filament production and recycling.

Chapter 2

Literature Review of the Extruder Mechanisms

Plastic recycling is like a magnificent alchemical journey, where discarded scraps and waste plastics are transformed into treasures of utility and beauty. It is a transformative process that breathes new life into these forgotten materials, shaping them into useful products that can be entirely unrecognizable from their original form. As we delve deeper into the world of plastic recycling, we encounter a captivating tapestry of alternative methodologies, each classified by the unique masterpiece they create from the recycled plastic canvas. For example: [1]

Primary recycling:

Primary recycling, like a captivating dance of reincarnation, breathes new life into recovered plastic, allowing it to shine once again in products that match the performance of those made from virgin plastics. It embodies the concept of closed-loop recycling, where the revived material returns to its original application, forming a seamless circle of sustainability. An enchanting example of primary recycling is the transformation of postconsumer PET bottles into fresh, gleaming bottles, preserving their essence and purpose.

Secondary recycling:

Secondary recycling, a mesmerizing act of adaptation, takes recovered plastic on a journey of reinvention. The material finds its place in products that may have slightly fewer demand requirements compared to its original application. Through a magical process of reformulation, plastic transcends its previous limitations, embracing a new role in the world. Imagine the graceful transformation of mixed polyolefins into vibrant flooring tiles, where their colorful presence enhances spaces with both beauty and sustainability.

Tertiary recycling:

Tertiary recycling, a realm of alchemy and innovation, takes waste plastic on a voyage of transformation into valuable chemicals and fuels. It is a process where plastic, like a phoenix rising from the ashes, becomes the raw material that generates a new generation of substances. Witness the mesmerizing glycolysis of PET, as it metamorphoses into diols and dimethyl terephthalate, the building blocks that weave the fabric of virgin PET, embodying the spirit of rebirth and resourcefulness.

Quaternary recycling:

Quaternary recycling, a powerful spectacle of energy reclamation, captures the essence of waste plastic as a potent source of fuel. It harnesses the energy locked within, giving it purpose and vitality through controlled incineration. Like tire-derived fuels igniting the flames of sustainable power, quaternary recycling embodies the fusion of environmental responsibility and energy generation, a captivating performance that leaves no waste behind [1].

The growing public demand for reduced plastic waste in landfills and the evolving political climate have highlighted the pressing need to recycle plastic scrap. However, for recycling to be more than a temporary solution, it must meet three crucial criteria: financial viability, technical feasibility, and environmental safety. Recyclers, both in the United States and globally, are businesses first and foremost. They can only continue diverting plastics from landfills if they can turn a profit by recycling what others discard.

Initially, the focus of recycling technology has been on recovering value from homogeneous, high-value, low-contamination plastic streams. This "low-hanging fruit" has been successfully recovered, assuming the necessary collection and reprocessing infrastructure is in place. Some manufacturers have also found applications for recycled plastics in less demanding uses. However, there are still several types of plastics that cannot be economically recycled, and this situation fluctuates daily due to changes in the price of natural gas.

The production cost of virgin plastics is expected to decrease as new, low-cost sources of natural gas, produced through fracking, come into play. This price reduction may further diminish the economic attractiveness of certain recycling processes. As always, the recyclability of plastics varies. Some can be recycled, some can be recycled economically, and some can be recycled economically in large quantities. However, not all plastics fall into these categories, and the specific ones that do change based on external factors beyond the control of plastic recyclers.

As a result, many recyclers choose to focus on a limited range of plastics that offer the best prospects for recycling success. This approach allows them to navigate the ever-changing landscape of recycling dynamics and maximize their efforts in achieving sustainable recycling outcomes [1].

2.1 Effects of recycling on properties of 3D Printing filaments

Compared to glass and metal materials, plastic often requires more extensive processing to be effectively recycled. This is due to the challenges associated with mixed plastics, which typically exhibit poor mechanical properties stemming from weak interfacial adhesion. When different plastics are combined, the low entropy of mixing often hinders efficient blending unless the resins have nearly identical compositions. The melting and mixing of different plastic types tend to result in phase separation, where the plastics form distinct phases with weak interfaces at the boundaries. This phase separation leads to structural weaknesses in the final compound, rendering mixed and untreated polymer blends suitable for only limited applications.

Given these complexities, the plastic recycling industry prefers to focus on primary recycling, which involves the recycling of single types of plastics. This approach yields greater financial returns and allows for more efficient and effective processing. By concentrating on primary recycling, recyclers can optimize their operations and generate the best possible outcomes in terms of both sustainability and profitability [1].

Polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are commonly used thermoplastic filament materials in 3D printing. While the cost of commercial filaments can be significantly higher than raw plastics, the recycling of these materials through thermo-mechanical processes can help reduce the overall cost of 3D printing. ABS, derived from oil, is used in various durable goods despite its toxic nature. On the other hand, PLA is a bio-based, biodegradable, and biocompatible polymer.

One of the drawbacks of PLA is its high sensitivity to elevated temperatures, which can lead to the degradation of its macromolecular structure, resulting in a decrease in PLA chain length with the number of injection cycles. However, shorter polymer chains have the ability to reorganize themselves into more ordered crystals, leading to a significant increase in melt flow rate. The tensile strength and tensile strain at break were slightly diminished compared to the tensile stress at break, with the largest decrease occurring after the first extrusion.

Recycling PLA can result in a marginal decrease in molecular weight after a single reprocessing step, but degradation increases as the number of cycles increases. Thermogravimetric analysis confirms a progressive weight loss during extrusion cycles, starting around 320 °C, with most weight evaporating after reaching temperatures beyond 600 °C. Thermo-mechanical recycling of PLA promotes transesterification in the presence of free radicals, leading to an increase in the transmission of water vapor (up to 40%) and oxygen (up to 20%) with the number of extrusion cycles. These agents serve as precursors of free radical reactions. Other forms of degradation may result from hydrolysis and transesterification with residual catalysts. The reduction in intrinsic viscosity during hydrolytic degradation is minor without the washing step, while significant viscosity decrease is observed in washed PLA wastes due to the influence of high temperature and shear stress during polymer reprocessing. Accelerated aging can also contribute to degradation.

To mitigate the reduction in mechanical strength caused by recycling, an addition of oxidative stabilizers (quinone) and residual catalyst stabilizers (tropolone) to neat PLA can significantly limit rheological degradation. Another approach involves coating the recycled polymer filament with polydopamine (PDA), which enhances its thermal stability up to 200 °C, increases tensile strength and strain at break, and improves surface adhesion.

Direct recycling of used PLA filament through grinding and re-extrusion into 3D printing filament has been proposed, with the material retaining similar diameter and surface finish after two extrusion cycles and one 3D printing process. However, there may be slight deterioration in mechanical properties due to chain scission during recycling, resulting in a reduction in viscosity. The rearrangement into a lamellar structure indicates randomization of polymer chains due to reduced molecular weight. The increment of crystallinity and the presence of pinholes in twice recycled PLA filament are attributed to the 3D printing process rather than repeated extrusion. Adding virgin PLA to the recycled and shredded PLA filament can improve viscosity, mechanical properties, and thermal properties, facilitating closed-loop recycling. This remediation process can be carried out using a bench-top machine at home [4].

2.2 Applications of PLA

Indeed, PLA-based materials have found applications in various markets, including biomedical, textile, and packaging industries.

In the biomedical field, PLA is commonly used due to its biocompatibility and biodegradability. It has been utilized in the production of medical implants, drug delivery systems, and sutures. PLA-based materials can be moulded into various shapes, such as blow-moulded bottles and injection-moulded cups, spoons, and forks. These products offer advantages in terms of being lightweight, durable, and environmentally friendly.

In the textile industry, particularly in Japan, PLA fibers have gained popularity. These fibers can be used to create fabrics for clothing, home textiles, and industrial applications. PLA fibers exhibit properties similar to conventional polyester fibers but with the added benefit of being derived from renewable resources.

PLA is also widely used in the packaging industry, particularly for short-term applications and food packaging. Thermoformed cups and trays made from PLA provide a sustainable alternative to traditional plastic packaging. PLA films are used for wrapping food products and can also be utilized as coatings for paper and cardboard packaging. Additionally, various moulded articles, such as disposable cutlery and food containers, can be manufactured from PLA.

These applications highlight the versatility of PLA-based materials across different industries. PLA's biodegradability and renewable nature make it an attractive choice for sustainable and environmentally friendly products [4].

2.3 Biomedical Applications

PLA-based materials have been extensively studied and developed for various medical applications due to their bioresorbable and biocompatibility in the human body.

Fracture fixation devices, such as screws and plates, have been produced using PLA-based materials. These implants are designed to gradually lose rigidity over time, allowing for stress to be gradually transferred to the healing bone and reducing the stress-shielding effect. PLA resorbs or degrades in the body, but its mechanical properties are lost within a few weeks. To address this, researchers have explored the use of resorbable PLLA fibers and calcium phosphate-based glass fibers to reinforce PLA matrices, creating fully resorbable composites with improved mechanical properties.

One advantage of resorbable composite prostheses is that they do not require a second operative procedure for removal, as metallic or non-resorbable implants do. However, there are concerns regarding the long-term effects of resorbed products and the presence of biostable or slowly eroding fibers in living tissues, which require further investigation.

PLA fibers have also found success as resorbable sutures, with copolymers of glycolide (GA) and l-lactide being commercially available. PLA fibers can be produced using solvent or melt-spinning processes and can be drawn under different conditions to orient the macromolecules, enhancing their mechanical properties.

Micro- and nanoparticles based on PLA have been utilized as drug delivery systems in medicine. PLA's hydrolytic degradability and low toxicity make it suitable for this purpose. The drug release rate and matrix degradation rate of these particles are influenced by their design and material properties. Copolymers of GA and rac-lactide have shown promise as drug delivery matrices.

Porous PLA scaffolds have also been investigated as reconstruction matrices for damaged tissues and organs. Various manufacturing techniques have been reported for the production of these materials, enabling control over scaffold porosity, pore size, and mechanical properties.

Overall, PLA-based materials have shown great potential in various medical applications, including fracture fixation, sutures, drug delivery systems, and tissue reconstruction matrices, owing to their biocompatibility and resorbable nature. Continued research and development in this field aim to improve the mechanical properties and long-term performance of these materials [4].

2.4 Packaging Applications

PLA has emerged as a viable alternative for packaging materials, offering better mechanical properties compared to polystyrene and properties similar to those of PET (polyethylene terephthalate). Market studies indicate that PLA is economically feasible for packaging applications, making it the most significant market in terms of volume for biodegradable packaging.

Initially, due to its higher cost, PLA was primarily used in high-value applications such as films, rigid thermoforms, food and beverage containers, and coated papers. One of the early adopters of PLA packaging was Danone, which used it for yoghurt cups in the German market.

Over the past decade, the use of PLA in packaging has increased in Europe, Japan, and the US, particularly in the area of fresh products. PLA is employed as a food packaging material for short-shelf-life products like fruits and vegetables. Its applications in packaging include containers, drinking cups, sundae and salad cups, sweet wrappers, lamination films, blister packages, and water bottles. Currently, PLA is also utilized in compostable yard bags to support composting programs at a national or regional level. Additionally, there is ongoing exploration of new applications such as cardboard or paper coatings, particularly in the fast-food market for items like cups and plates.

However, for PLA to cater to a larger market, certain drawbacks need to be addressed. These include limited mechanical properties, barrier properties, heat resistance, and the need to substantially increase world production of PLA to meet market expectations. Ongoing research and development efforts aim to improve these aspects and enhance the overall performance of PLA as a packaging material.

2.5 Main Theme

A 3D printing filament recycler typically consists of the following components:

1. Shredder

2. Extruder

3. Cooling System

4. Diameter Measuring Unit

5. Spooling

2.5.1 Shredder

The working of a shredder specifically designed for shredding wasted 3D prints and support structures is a fascinating process that involves cutting-edge technology and precise engineering. This innovative machine is designed to efficiently break down and transform discarded 3D prints and support structures into smaller, more manageable pieces, enabling easier recycling and repurposing. Let's delve into the inner workings of this shredder and explore the steps involved in its operation.

At the heart of the shredder lies a robust cutting mechanism, typically equipped with sharp blades or cutting edges. The 3D prints and support structures are fed into the shredder through a hopper, where they are guided towards the cutting mechanism. As the materials enter the cutting chamber, the powerful blades go into action, slicing through the waste with precision and force.

The cutting mechanism is carefully engineered to handle the unique characteristics of 3D printed materials, which can vary in composition and hardness. The blades are designed to withstand the demands of shredding these materials effectively, ensuring a consistent and efficient process. Their sharpness and durability allow them to effortlessly slice through the waste, reducing it to smaller fragments.

As the cutting process progresses, the shredded 3D print and support structures are directed towards a collection system. This system can consist of a container or a conveyor belt, which gathers the shredded material for further processing or recycling. The collection system ensures that the shredded waste is efficiently contained, preventing dispersion, and facilitating easy handling.

Safety features are an essential aspect of the shredder's design. Emergency stop buttons, safety guards, and overload protection mechanisms are implemented to ensure the well-being of users and prevent accidents. These safety measures provide peace of mind and create a secure working environment for operators.

The shredder's operation can be controlled through an intuitive control panel. This panel allows users to monitor and adjust various parameters, such as feed speed and cutting intensity, to achieve optimal shredding results. The user-friendly interface simplifies the operation and provides flexibility to adapt the shredder's performance to different types of waste materials.

The shredded 3D prints and support structures produced by the shredder hold tremendous value for recycling purposes. These smaller fragments are easier to handle and process, making them suitable for various recycling methods, such as filament production or material reprocessing. By transforming wasted 3D prints and support structures into smaller shreds, the shredder contributes to the efficient utilization of resources and promotes sustainable practices within the 3D printing industry.

In summary, the working of a shredder used for shredding wasted 3D prints and support structures involves a powerful cutting mechanism, safety features, and a collection system. By effectively reducing the size of the waste, the shredder facilitates recycling and repurposing, leading to a more sustainable approach to 3D printing. Its precision and efficiency make it an indispensable tool for managing 3D printing waste and promoting environmental stewardship in the additive manufacturing field. Unfortunately, the fabrication of the shredder was postponed due to lack of funds and the wasted 3D prints were shredded using third party sources.

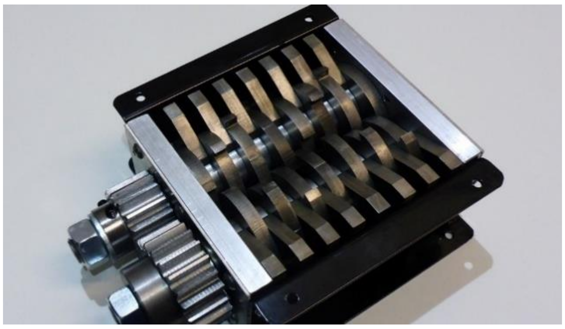

Figure 1: Shredder

2.5.2 Extruder

Extruders are essential machines in the plastic processing industry, and their key components work together to transform plastic materials. Here are the main components and their functions:

1. **Drive System:** The drive system provides the power and stability for the extruder's operation. It typically consists of a motor, gear box, bull gear, and thrust-bearing assembly. The motor provides rotational power, which is transmitted through the gear box to drive the screw. The bull gear and thrust-bearing assembly help maintain the alignment and support of the rotating components. Some extruders utilize direct drive systems, which eliminate the need for a gear box and simplify the setup.
2. **Feed System:** The feed system is responsible for conveying the solid resin into the extruder. It comprises the feed hopper, feed throat, and screw feed section. The solid resin is gravity-fed into the feed hopper and then enters the feed throat, where the screw starts to convey and transport the resin forward. The screw, along with the barrel and heating systems, gradually heats and melts the resin, preparing it for extrusion.
3. **Heating System:** The heating system consists of heaters and temperature control devices installed along the barrel of the extruder. The heaters provide controlled heat to melt the plastic resin inside the barrel. Precise temperature control is crucial to achieve the desired melt viscosity and consistency for the extrusion process.
4. **Screw and Barrel:** The screw and barrel are the core components responsible for melting, mixing, and conveying the plastic material. The screw rotates within the barrel and transports the plastic resin forward, creating the necessary pressure and shear to melt and mix the material thoroughly. The design of the screw, including its flight geometry and channel depth, can be customized for different materials and applications.

5. **Die and Adapter:** The extrudate, the molten plastic material, passes through the adapter before reaching the die. The adapter helps shape and distribute the molten plastic evenly as it transitions from the screw flight to the die. The die is a specially designed opening that imparts the desired shape and size to the extruded material. It can be customized for different product profiles, such as pipes, sheets, or profiles.
6. **Control System:** The control system manages and regulates various parameters during the extrusion process. It controls the motor speed (rpm), barrel temperatures, and other process conditions. Advanced control systems incorporate sensors and feedback loops to monitor melt temperatures, pressures, and product quality. They make real-time adjustments to feeder settings, puller speeds, and screw speeds to ensure consistent and high-quality extrusion.

Extruders come in various sizes, typically categorized by the diameter of the screw or barrel and the length-to-diameter ratio (L/D). Standard extruder sizes range from small diameters (e.g., 1 inch or 25 mm) up to larger diameters (e.g., 10 inches or 250 mm). Larger extruders can be custom-built to meet specific customer requirements.

These components and systems work together to facilitate the extrusion process, transforming plastic materials into various forms such as pipes, sheets, profiles, and more.

The extruder L/D (length-to-diameter) ratio describes the relative lengths of the screw and extruder barrel. It is a crucial parameter that affects the extrusion process and throughput capacity.

Throughput, or the amount of material processed by the extruder per unit of time, is indeed directly related to the extruder L/D. Two extruders with the same diameter but different L/D ratios will have different throughput capacities.

Longer extruders with higher L/D ratios have more melting and mixing capacity. The increased length allows for more efficient melting and better mixing of the material, which facilitates higher processing rates. The extended residence time in the extruder enables better heat transfer, more uniform melting, and improved homogeneity of the melt.

On the other hand, shorter L/D extruders have advantages such as requiring less floor space, lower initial investment costs, and lower replacement part costs for screws and barrels. They also offer shorter residence times, which can be beneficial when processing temperature-sensitive materials.

It's important to consider the specific requirements of the application when choosing the appropriate extruder L/D ratio. Longer L/D ratios are generally favoured for higher throughput and improved melt quality, while shorter L/D ratios may be more suitable for specific constraints or material characteristics.

. Short L/D extruders have the following advantages:

- Space Savers.
- Cost Effective.
- Easy Maintenance.
- Delicate Material Guardians
- Low Torque.
- Easy Customization.

Longer L/D extruders have the following advantages:

- Magnificent Throughput.
- Mixing Mastery.
- Mixing Mastery.
- Melting Marvels.
- High Conductive Heating.

Within the realm of extruders, various L/D ratios grace the stage, offering a range of possibilities. Common ratios include 18:1, 20:1, 24:1, 30:1, 36:1, and 40:1, each presenting its unique characteristics. With the knowledge of the L/D ratio, one can unlock the mystery of the barrel length, unraveling the secrets hidden within. Moreover, throughput rates dance in perfect harmony with the screw diameter, showcasing a direct proportionality. It is a mesmerizing spectacle where larger diameter extruders take center stage, commanding a greater output. For a visual representation, one can explore the insightful throughput charts illustrating the capabilities of diverse single screw extruders of different sizes.

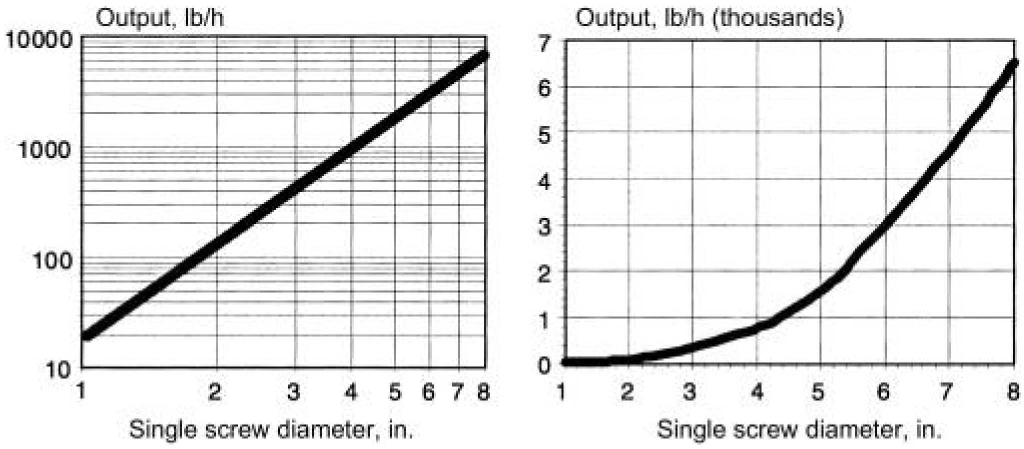

Figure 2: Graph of ratio L/D of lead screw.

In the captivating realm of single-screw extruders, a symphony of components harmoniously unites to bring forth the magic of plastic transformation. At the core lies a hollow cylindrical barrel, its external surface adorned with heaters that emanate warmth and vitality. To safeguard against the relentless passage of time, the inner surface of the barrel is adorned with a resilient metal liner, such as the esteemed Xaloy, ensuring a steadfast resistance to wear and tear. For enhanced durability, the screw flights are graced with a compatible alloy hard wear surface, fortifying their resilience against the forces at play. With meticulous precision, a screw takes its rightful place within the cylinder, its geometry tailored to suit the polymer and the desired thermal conditions of the molten melt. This intricate dance of design choices determines the very essence and ultimate performance of the extrusion system, rightfully earning the title of the heart of the process. Driven by an electric motor, the screw spins with purpose, propelled by a gear reducer thoughtfully sized to match the speed and power requirements of this instrumental component. With elegance and finesse, a barrier screw design emerges, harnessing the intrinsic melting mechanism within the extruder to elevate efficiency to new heights. While the motor supplies the majority of the energy needed to melt the polymer, the barrel temperature remains under careful guardianship. Electric heaters, woven into the fabric of the extruder, diligently maintain the optimal temperature, their ingenuity often complemented by cooling water channels that gracefully traverse the landscape.

It is within this magnificent interplay of components and the orchestration of heat, motion, and material that the single-screw extruder breathes life into the art of extrusion, crafting marvels from formless polymer streams [1].

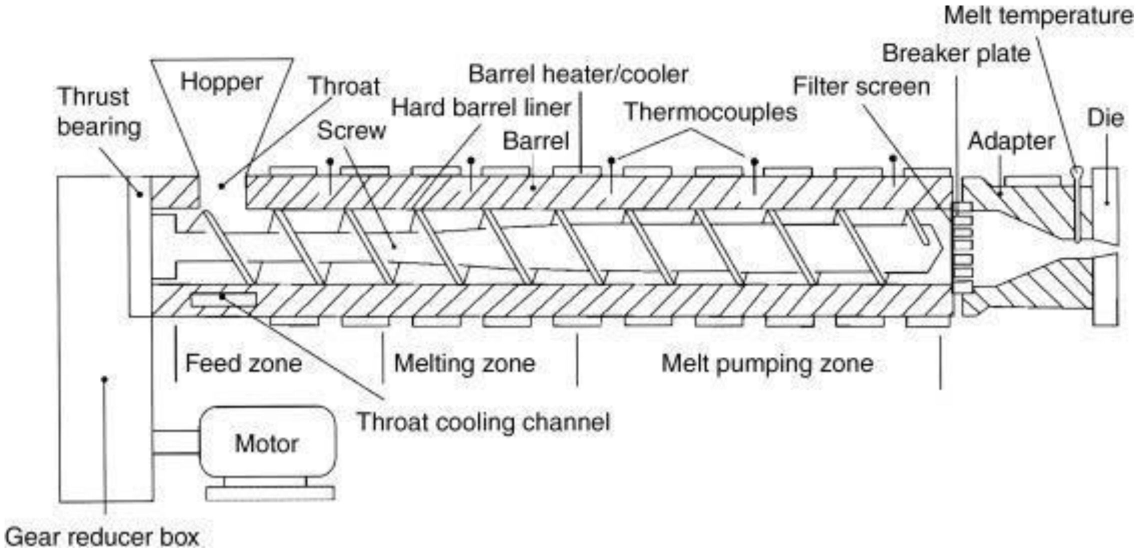

Figure 3: Cross section of an extruder [1].

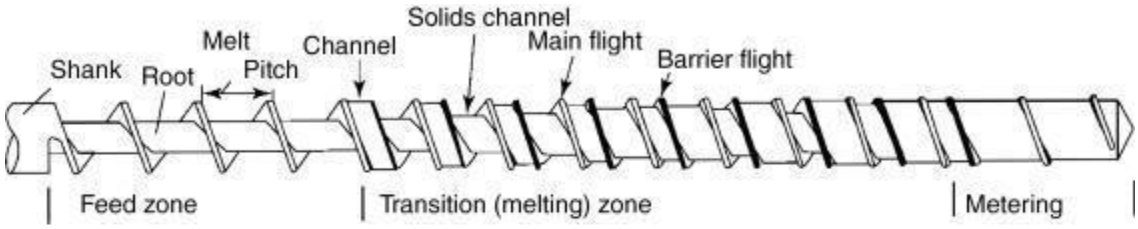

Figure 4: Schematic of Barr barrier flight screw [1].

The mesmerizing dance of the extrusion process commences as the solid polymer makes its grand entrance through the feed throat, embarking on a transformative journey within the extruder's domain. Guided by the turning motion of the screw, the polymer is gently conveyed and compacted into a solid plug, ready to undergo its metamorphosis. A captivating interaction unfolds as the plug encounters the fiery embrace of the hot barrel surface, where heat and pressure conspire to melt the polymer, bestowing it with a molten essence.

The screw, adorned with its flights, assumes the role of a diligent collector, diligently gathering the molten polymer from the barrel's surface. With each revolution, the screw propels the melt towards the extruder's end, a place of culmination where complete melting is achieved. Yet, this process is not solely one of transformation, but also one of fusion and blending. The screw's unwavering rotation serves as the catalyst for the intricate dance of mixing, ensuring the homogeneity and quality of the melt that courses through the extruder's veins.

The significance of the melt cannot be understated, for it holds the key to product quality and process stability. Its characteristics bear influence on crystallization behaviour and molecular weight, shaping the final form of the polymer's creation. Within the depths of the extruder, a fascinating interplay of mechanical energy and viscous dissipation occurs. The polymer's high viscosity, ranging from 50 to 1000 Pa, grants a stage upon which vast amounts of mechanical energy dissipate within the thin layer of molten polymer. As the motor turns the screw, propelling the polymer plug against the heated barrel surface, this mechanical energy metamorphoses into heat through the enchanting phenomenon of viscous dissipation.

The radiant heat within the melt film burgeons, nurtured by thermal conduction and convection, imparting its transformative warmth to the solid polymer plug, the very essence of the barrel, and the mesmerizing pool of molten polymer. Yet, caution must be exercised, for excessive temperatures and mechanical exertion can sow the seeds of degradation—be it thermal, oxidative, or mechanical in nature—posing a threat to the polymer's integrity.

In this delicate balance between heat, energy, and polymer, the extrusion process unfurls its grand symphony. It is a world where solid becomes molten, where mechanical energy ignites the flames of transformation, and where the quality of the melt sets the stage for the wonders that await beyond the die. Within this intricate dance, the extruder holds the power to shape the very essence of the polymer, birthing creations that embody the perfect union of form, function, and stability [1].

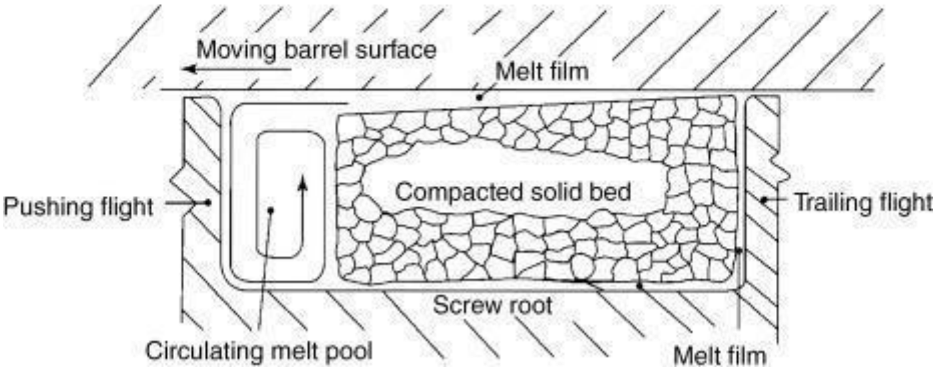

Figure 5: Melting mechanism of single-screw extruders [1].

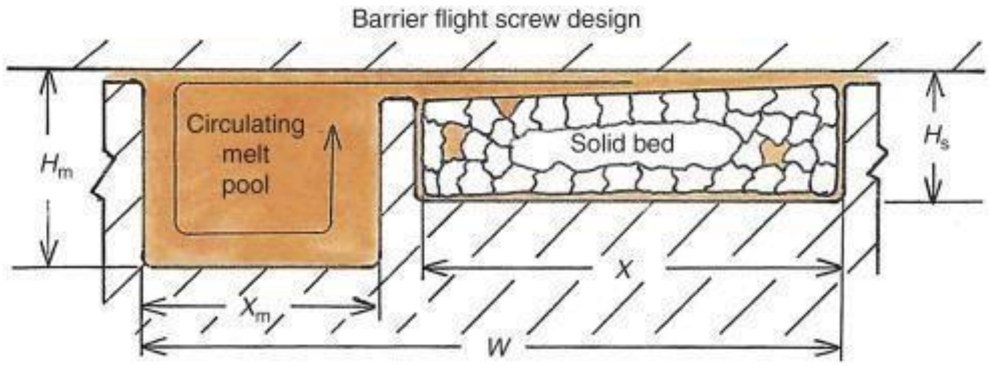

Figure 6: Schematic diagram of barrier screw cross section [1].

A new era emerges with the advent of energy-efficient screw designs. These innovative creations revolutionize the process by ingeniously manipulating the melting mechanism, leading to a reduction in melt temperature and an unprecedented level of efficiency. The key lies in the intentional disruption of the traditional melting process, paving the way for a remarkable transformation.

Within the heart of these pioneering screw designs, a pivotal moment arises when the screw geometry is altered to foster the fusion of collected melt with the solid particles of the compacted bed. This ingenious approach facilitates the transfer of thermal energy, as the high-temperature melt conducts excess energy to the low-temperature unmolten solid. This intricate dance of conduction works harmoniously, resulting in a lower average temperature above the polymer's melting point. However, the quest for temperature homogeneity persists, beckoning the need for further innovation.

Enter the stage, the sections of the screw specifically crafted to remix and shear the melt, forging a symphony of uniformity in temperature. These masterful screw design sections serve as the catalysts that mold the melt into a homogeneous state, ensuring every molecule basks in the same thermal embrace. Aptly referred to as "Energy Transfer" screws, these marvels of engineering push the boundaries of what is possible. Among their illustrious representatives, the ET and Double Wave screw designs stand tall, bearing testament to the ingenuity and tireless pursuit of excellence.

While the majority of extruder screws boast a single metal ridge, akin to a grand screw thread wrapped around a cylindrical root, a select few break free from convention. These rebels of the extrusion world embrace multiflight designs, featuring more than one helical flight, often two or three. This departure from the norm bestows upon them a unique identity, enabling them to unleash a different dimension of performance and capability.

With their orientation, whether right-handed or left-handed, aligned with the rotation direction of the screw, these screws bring forth a mesmerizing interplay of motion and power.

As the extrusion process unfolds, the stage is set for the grand performance. Energy-efficient screw designs take centre stage, their choreographed movements transforming the very essence of melting, mixing, and homogeneity. With each revolution, they orchestrate a symphony of thermal equilibrium, harnessing the power of innovation to unlock new realms of efficiency and productivity. In this realm of extrusion, where revolutions and creativity intertwine, the single-screw extruder emerges as a beacon of ingenuity, shaping the future of polymer processing with its unwavering dedication to precision and performance [1].

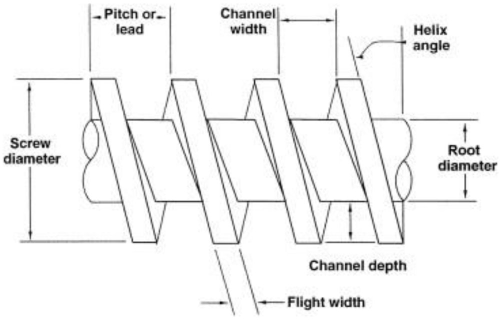

Figure 7: Feed screw nomenclature [1].

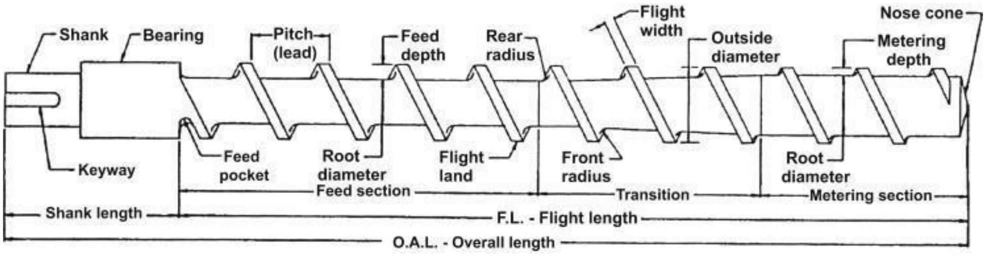

Figure 8: Geometrical attributes of a screw [1].

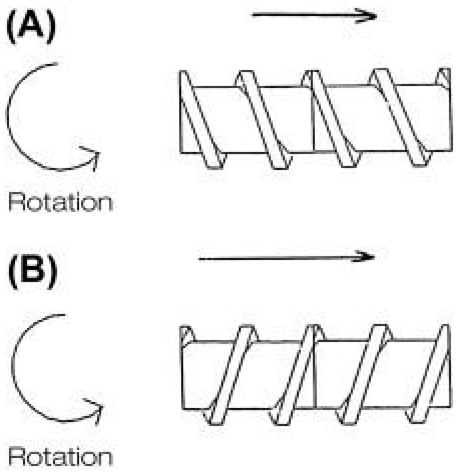

Figure 9: (A) Right-handed screw [1]. (B) Left-handed screw [1].

The stationary barrel and the turning screw create a symphony of forward movement. As the screw rotates, frictional forces come into play, propelling the material on its journey. The rate of output is delicately controlled by the feed screw's intake capacity, a crucial determinant of productivity. In most cases, the flights in the feed section are filled to the brim, a phenomenon known as flood feeding. This flood of material encounters the warmth emanating from the barrel heaters, causing it to gradually heat up as it progresses.

With each step forward, a remarkable transformation takes place. As the material surpasses its melting point, a thin film of molten polymer forms along the barrel's surface. The journey continues, and the volume of the melted component steadily increases until the entire material is immersed in a state of molten bliss. In the final act of the extruder, the pumping section takes the stage, exerting pressure on the polymer melt, propelling it with determination toward the awaiting die.

While the single-screw extruder gracefully orchestrates a degree of end-to-end mixing, the residence time of the melt within its confines is relatively brief, typically lasting around 10 seconds. Nevertheless, this intricate dance of mixing proves to be remarkably effective, particularly when encountering high back pressure. In these instances, the extruder assumes the role of a distributive mixer, skilfully blending and dispersing the components on a small scale. It becomes a compounding device of great value, capable of seamlessly incorporating masterbatch or refining the outputs of an intensive high-speed mixer handling powders.

To overcome inherent design challenges within single-screw extruders, ingenious minds have introduced feed screw mixing devices. These innovative creations, such as mixing pins, Dulmage sections, Dray Mixers, and Maddock Mixers, serve as transformative agents, enhancing the extrusion process. Representing diverse modifications of the screw, they offer localized solutions to improve mixing efficiency and product quality. Like masterpieces on display, these intricately crafted modifications redefine the possibilities within the extrusion realm, shaping the future of polymer processing one innovation at a time [1].

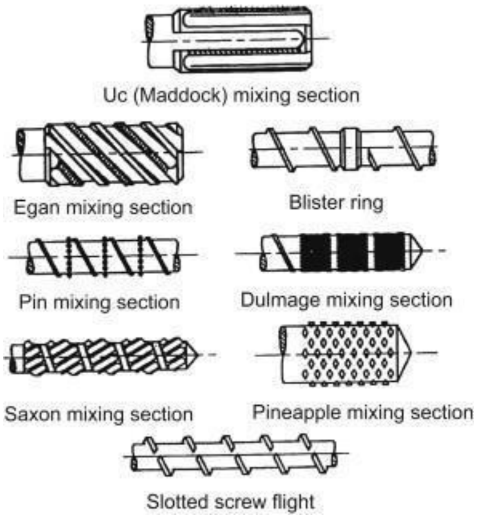

Figure 10: Local screw modifications [1].

The screw, a vital entity that holds the power to shape the performance of the entire extruder. With its intricate design, the screw governs the ultimate goal of delivering a homogeneous molten polymer, precisely meeting the required rates, pressures, and melt temperature levels with unwavering stability.

In the realm of single-screw extruders, the screw design unfolds in three fundamental sections: the feed section, transition section, and metering section. Each segment plays a crucial role in the intricate dance of material transformation.

The feed section sets the stage for the material's entry into the extruder, providing the initial impetus for forward movement. It establishes the foundation for the subsequent stages, ensuring a consistent and controlled flow of the polymer.

Transitioning seamlessly, the material enters the transition section, where a delicate transformation takes place. Here, the screw gently guides the material from its solid form towards a molten state, preparing it for the forthcoming journey.

As the material progresses, it reaches the metering section, where the screw assumes its final act of precision. With meticulous calculation, the metering section regulates the flow rate, maintaining a harmonious balance between the polymer's movement and the desired output.

Accompanying the single-screw flight is a helix angle of 17.7°, meticulously selected to yield a screw pitch equal to the diameter of the screw. This remarkable configuration, known as the "Square Pitch" design, ensures a harmonious interaction between the screw and the material, facilitating efficient melting, mixing, and extrusion.

The symphony of the extrusion process relies on the ingenuity of the screw design. Its precise geometry and well-orchestrated sections harmonize to create a masterpiece of extrusion, where the transformation of solid polymer into a homogenous molten state takes centre stage. With every rotation, the screw breathes life into the extruder, pushing boundaries and unlocking the full potential of polymer processing [1].

The extruder L/D (length-to-diameter) ratio describes the relative lengths of the screw and extruder barrel. It is a crucial parameter that affects the extrusion process and throughput capacity.

Throughput, or the amount of material processed by the extruder per unit of time, is indeed directly related to the extruder L/D. Two extruders with the same diameter but different L/D ratios will have different throughput capacities.

Longer extruders with higher L/D ratios have more melting and mixing capacity. The increased length allows for more efficient melting and better mixing of the material, which facilitates higher processing rates. The extended residence time in the extruder enables better heat transfer, more uniform melting, and improved homogeneity of the melt.

On the other hand, shorter L/D extruders have advantages such as requiring less floor space, lower initial investment costs, and lower replacement part costs for screws and barrels. They also offer shorter residence times, which can be beneficial when processing temperature-sensitive materials.

It's important to consider the specific requirements of the application when choosing the appropriate extruder L/D ratio. Longer L/D ratios are generally favoured for higher throughput and improved melt quality, while shorter L/D ratios may be more suitable for specific constraints or material characteristics.

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2.5.3 Mixing

Within the intricate workings of the extruder, an additional critical function comes to light, even when processing a single stream of virgin polymer. This function is none other than mixing, which takes on two distinct forms: distributive mixing and dispersive mixing.

Distributive mixing, as its name suggests, operates to evenly distribute particles throughout the melt. Its purpose is to ensure a uniform dispersion of various components within the molten polymer. This low-shear process achieves its magic by continuously altering the flow directions, fragmenting the molten polymer into channels, and skilfully recombining the melt. Distributive mixing finds its applications in scenarios involving fibers, reinforcing fillers, shear-sensitive materials, and the quest for uniformity in melt temperature.

On the other hand, dispersive mixing emerges as a forceful entity, breaking up agglomerates and large particles, dispersing them evenly throughout the melt. This high-shear process exerts significant shear stress as the molten polymer is compelled through minuscule openings, resulting in the generation of shear heat. Dispersive mixing finds its purpose in the realm of alloying different plastics, pigment dispersion, and the blending of non-reinforcing fillers and additives. These additives include flame retardants, impact modifiers, and lubricants, all of which benefit from the intense shearing forces to achieve a uniform and thorough integration into the melt.

In this intricate dance of mixing, both distributive and dispersive forms find their place, working in harmony to create a balanced and homogeneous blend. They facilitate the even distribution of particles, the breakdown of agglomerates, and the dispersion of additives, ensuring that every element is incorporated seamlessly within the molten polymer. Whether it's the quest for uniformity, the desire to enhance material properties, or the need to achieve specific characteristics, the dual forces of distributive and dispersive mixing come together, leaving no particle unattended and no additive unblended.

The extruder, in its mastery of mixing, breathes life into the polymer processing realm, transforming raw materials into exquisite blends with precision and finesse. It is within the controlled chaos of distributive and dispersive mixing that the true magic of the extrusion process unfolds, bringing forth a world of endless possibilities for the world of plastics [1].

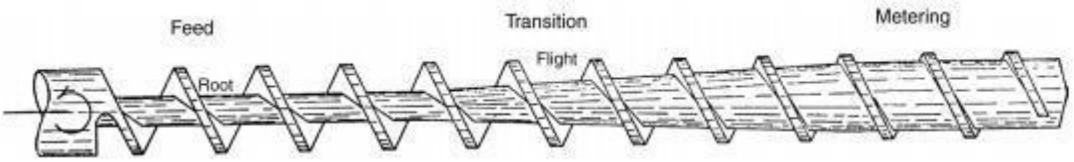


Figure 11: Regions in lead screw [1].

To achieve the ultimate goal of a uniform melt temperature and a homogeneous melt in single-flight screw designs, the inclusion of a mixing head alongside the screw proves to be indispensable. The effectiveness of mixing is determined by two crucial factors: residence time and shear rate experienced by the fluid in the mixing section.

Given that polymer mixing flows exhibit a laminar nature, the degree of distributive mixing relies on the number of flow direction changes. Distributive mixing sections play a vital role in dividing the flow into multiple channels, recombining them, and breaking them apart, all in an effort to enhance temperature homogeneity. As the material enters the mixing section, the flow is meticulously fragmented from a single large channel or flow front into numerous small channels or flow fronts. These flow fronts then reunite and are subsequently redistributed into smaller flow channels, repeating the process of recombination. Alternatively, other distributive mixers employ obstacles within the screw channel to induce changes in the direction of polymer flow, accomplishing the desired degree of mixing.

On the other hand, achieving dispersive mixing necessitates high shear rates and shear stresses, which are attained by forcefully directing the melt over a constraining barrier. Dispersive mixing sections demand more energy compared to distributive mixing. This higher energy input carries the risk of raising the polymer melt temperature or potentially causing degradation.

The careful balance between distributive and dispersive mixing is paramount in the extrusion process. Distributive mixing sections ensure the even distribution of particles and temperature throughout the melt, while dispersive mixing sections focus on breaking down and dispersing agglomerates and additives. The combination of these mixing mechanisms aims to create a melt that is not only uniform in temperature but also homogeneous in its composition, enabling the extrusion process to produce high-quality products.

As the polymer flows through the extruder's intricate pathways, the mixing head and its associated sections orchestrate a symphony of flow direction changes, channel divisions, recombination, and flow disruptions. This intricate dance of mixing promotes the transformation of raw materials into a cohesive and well-blended melt, setting the stage for the subsequent shaping and forming processes.

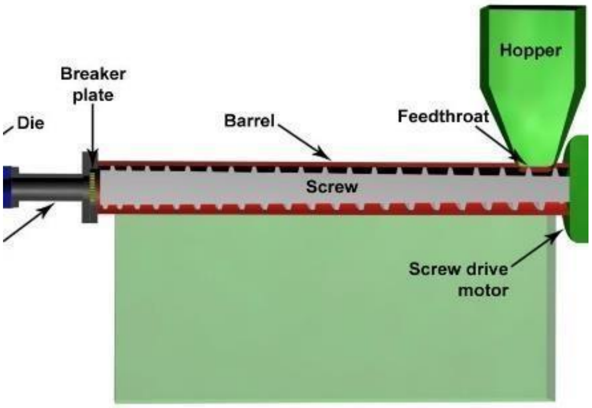


Figure 12: Extruder Mechanism.

2.5.4 Single-Screw Extruder Mechanism

The fundamental mechanisms that drive the process can be classified into three main functions: solids conveying, melting or plastination, and melt pumping. These mechanisms work in harmony, and their combination forms the extrusion model for the single screw, which will be further explored in subsequent sections. It is crucial for readers to grasp the operational principles underlying each of these primary functions - conveying, melting, and metering - as it greatly aids in comprehending the extrusion process.

Solids conveying involves the movement of solid materials within the extruder. It pertains to the transfer of raw polymer solids from the feed throat towards the screw. The extruder's design facilitates the efficient conveyance of the solid particles, ensuring a steady flow towards the melting zone.

Melting, or plastination, is the process by which the solid polymer particles are transformed into a molten state. As the solid particles are conveyed towards the melting zone, they encounter the heated barrel surface. The heat generated by the barrel's external heaters gradually raises the temperature of the solids, leading to their softening and eventually melting. The molten polymer is collected and transported by the screw flights towards the end of the extruder.

Melt pumping refers to the pressurization and pumping of the molten polymer through the die. As the molten polymer reaches the end of the screw, it undergoes further mixing and is pressurized to generate the necessary force for extrusion. The pressurized melt is then propelled through a die, which shapes it into the desired form or profile.

It is crucial to recognize that extruders are primarily limited by the melting process. Understanding the distinctions between solids conveying, melting, and metering is vital for optimizing the design and performance of the extruder screw. By comprehending the nuances of melting and its differentiation from the other functions, one can harness the full potential of an extruder, leading to improved efficiency and better utilization of the chosen screw design.

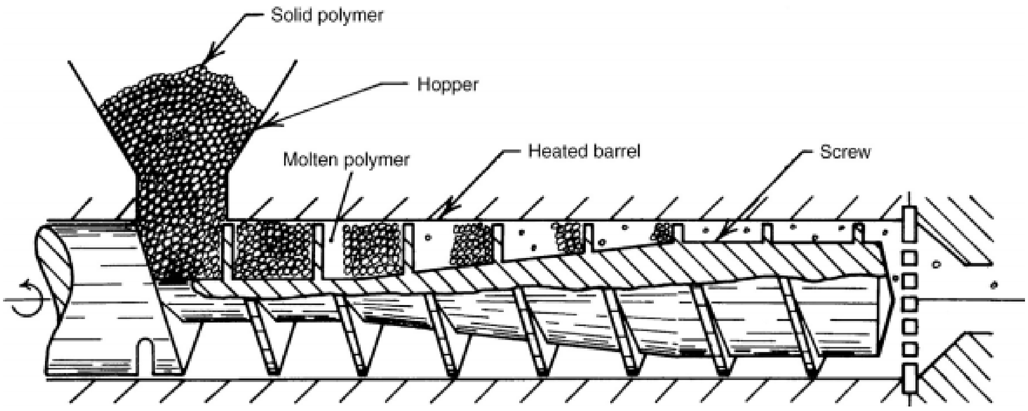


Figure 13: Cross-section through an operating extruder [1]

The process of plastination refers to the mechanical conversion of solid polymer into a molten polymer. While some polymers may exhibit crystalline structures and possess a distinct melting point, others, particularly amorphous or glassy polymers, undergo a transition from a solid glass state to a liquid melt at a temperature known as the glass transition temperature. Semicrystalline polymers, on the other hand, have both a melting point for the crystalline regions and a lower glass transition temperature for the non-crystalline portions.

In Figure 14, a cross-section of a single-screw extruder is depicted. The extruder receives the solid polymer in granular form from the hopper. The screw is responsible for picking up the polymer and conveying it into the extruder. As the polymer advances, it experiences compaction due to the frictional forces generated during solid conveying. The compacted solid forms a compressed plug that rubs against the extruder barrel. This rubbing action generates heat, which, combined with the heat conducted from the barrel heaters, raises the temperature of the barrel surface above the melting or softening point of the polymer.

As the barrel moves relative to the solid, the energy from the motor is dissipated into the thin film of polymer melt those forms on the barrel surface. The molten polymer is then scraped from the barrel and captured by the screw flights, which pump it towards the metering section and ultimately to the die. The formation of the melt pool pressurizes the screw flight and pushes the solid against the trailing flight, creating the melting system.

In the transition section, the screw must simultaneously convey solids, melt the polymer, and pump the melt formed during melting. The metering section is responsible for creating a circulating flow of melt by scraping the melt from the barrel and forcing it down to the bottom of the screw flight. Melt is conveyed through two mechanisms in the metering section: drag flow and pressure-driven flow. The balance between these two flows determines the final output of the metering section, which is controlled by the pressure difference between the inlet of the metering section and the die restriction at the end of the extruder.

The understanding of the extrusion and melting mechanisms has evolved over time. Early research focused on solid conveying and metering, which were studied independently. In the 1960s, Bruce Maddock conducted freezing experiments that revealed the melting mechanism described in Figures 6 and 14. This experimental work, combined with mathematical modelling by Tadmor and others, significantly advanced the understanding of extrusion and improved screw design methods.

Single-flight screws, however, had limitations in terms of output and melt homogeneity. To address these issues, the Maddock mixer, a dispersive mixing element, was introduced to capture unmelted polymer and improve melt quality. Additionally, the invention of the Barrier screw by Barr increased extrusion outputs and reduced melt temperatures compared to standard single-screw designs.

Further advancements in screw design aimed to disrupt the melting mechanism after partial polymer melting and promote mixing between the solid polymer and the hot melt. Examples of such designs include the HPM double wave screw and the Barr ET screw, which led to increased output, lower melt temperatures, and improved melt homogeneity.

These experimental discoveries and innovations in screw design have played a crucial role in advancing the field of extrusion and enhancing the performance and efficiency of extrusion processes [1].

2.5.5 Solid Feeding

In the feeding section of the extruder, the polymer is introduced into the screw from the hopper. The screw in this section acts as a volumetric feeder, meaning that with each revolution of the screw, a specific volume of polymer is swept out. The volume swept out is determined by factors such as the cross-sectional area of the screw flight, the discharge area of the hopper, and the number of screw revolutions.

The amount of polymer taken into the screw depends on the bulk density of the polymer granules and the rate at which they can fall into the screw as the screw flight passes under the hopper. As the screw flight moves beneath the hopper opening, it pushes the solid pellets forward and captures them at the leading edge of the barrel opening, which is referred to as the feed throat. Once the flight passes the trailing edge of the hopper opening, polymer pellets fall into the open screw channel and are pushed forward by the pushing edge of the screw flight.

Extruders can be designed with different types of feed openings, such as circular, rectangular, or tangential feed pockets. The efficiency of the screw filling process depends on the geometry of the opening and the speed of the screw. The screw speed determines the time it takes for polymer to fall into the screw, and it's important to note that the flight can also push polymer away from the opening, which is known as slinging. Slinging can reduce the amount of polymer picked up by each revolution of the screw.

To prevent the wedging of solid polymer between the screw flight and the barrel, which could cause the screw to stall, the screw flights in this section are undercut more than the nominal diameter of the screw. This ensures that there is enough clearance for the polymer to flow smoothly without causing blockages or hindering the movement of the screw [1].

2.5.6 Solid Conveying

As the polymer pellets are transported into the screw, they experience compression due to the feeding forces exerted by the screw. Eventually, these pellets come together to form a solid plug that completely fills the screw channel. At this stage, the feeding process is controlled by the relative friction between the polymer and the screw as well as the barrel, creating an unbalanced torque that drives the plug forward.

To optimize the feeding process, it is desirable to make the polymer stick to the barrel and slip on the screw. You can observe a similar principle by conducting a simple experiment using a threaded rod and a nut. Imagine the rod as the screw and your fingers as the barrel. Without touching the nut, rotate the rod, and you will notice that the nut simply turns with the rod. In this case, the polymer (represented by the nut) is sticking to the screw and slipping on the barrel (your fingers).

Now, touch your finger to the nut to prevent it from turning, simulating a scenario where the polymer is sticking to the barrel. As the rod turns, the nut will start to slip between the rod and the nut, advancing along the screw threads. This demonstrates the case where the polymer is sticking to the barrel. In the solids conveying of polymers, a similar mechanism occurs, but there will be some degree of slippage between the polymer and the barrel, allowing it to rotate and advance along the screw, tracing out a long helical path with a helix angle of theta (θ).

It's important to note that the amount of slippage between the barrel and the screw will determine the torque required to move the polymer (or nut) forward. Just like in the experiment, lubricating the rod would make it easier to move the nut, while a dirty or rusty rod would increase the amount of force required to move the nut forward. The same principle applies to the extrusion process, where reducing the friction between the polymer and the barrel improves the efficiency of feeding.

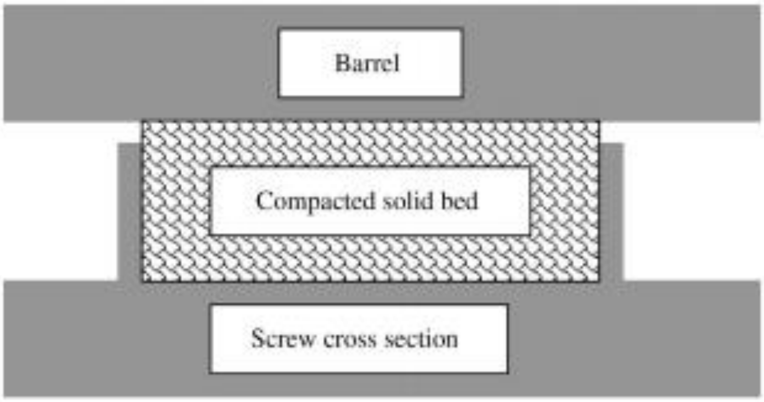


Figure 14: Cross-section through an operating extruder [1]

The motion of the polymer inside the extruder is influenced by the turning of the screw. As the screw rotates, the screw flight pushes the polymer, providing the energy required to move it down the helical screw channel. The polymer is constrained by the screw flights, which guide its motion. However, the movement of the solid polymer is impeded by frictional forces between the solid and the barrel, as well as between the solid and the screw surfaces. This prevents the polymer from simply sliding down the channel like a nut.

Due to the rotation of the screw inside the stationary barrel, the solid polymer undergoes a combination of axial and rotational motion. As it moves down the channel, it also rotates, resulting in a helical motion relative to the extruder barrel. The angle at which the solid polymer moves relative to the barrel with each rotation of the screw is referred to as the solids conveying angle (θ). Fig. 16 illustrates the relative motion of the solid plug in the screw channel and its motion relative to the barrel surface.

By determining the velocity at which the solid plug moves along the screw flight in a given time, it is possible to calculate the volumetric solids conveying rate. This calculation involves considering the screw geometry and the solids conveying angle. A derivation of this calculation was performed by Darnell and Mol (Eq. 1) [1].

$$\frac{Q}{H} = \frac{\pi^2 Dh(D-h)tan\theta tan\boldsymbol{\phi}}{tan\theta + tan\boldsymbol{\phi}} \qquad (1)$$

where Q, volumetric throughput; D, screw diameter; h, channel depth; N, screw speed. The mass flow rate, G, can then be calculated by multiplying the volumetric flow rate (Q) by the density of the solid bed (Eq. 2) [1]:

$$G = Q \times N \times Density\ of\ solid\ bed \qquad (2)$$

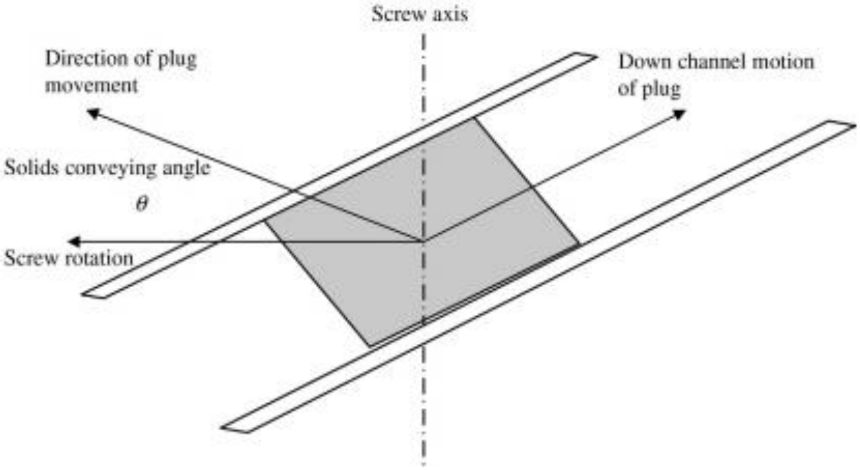


Figure 15: Motion of solid plug relative to barrel surface, angle θ, and down the channel relative to the screw and flight surfaces [1]

2.5.7 Melting Mechanism

In this section, we delve into the mechanism of melting in a single-screw extruder and explore the methods used to estimate the melting rate. In Fig. 6, we can observe the fundamental melting mechanism discovered by Bruce Maddock. In the development of these models, it is customary to assume that the screw and solid bed are stationary, while the barrel is moving at velocity V_b relative to them. This simplifies the mathematical analysis and does not impact the derived models.

Looking closely at Fig. 6, we see that the compacted solid bed is surrounded by molten polymer. The solid material, which was fed into the screw, has been tightly compressed by the feeding forces. As the metal surfaces of the screw and the barrel exceed the melting point of the polymer, the solid begins to melt while it moves along the screw. For now, we will focus on the upper melt film between the solid bed and the barrel surface and ignore the lower melt films formed in the regions between the solid and the screw. Although these lower melt films are important in terms of polymer degradation and contribute to the overall screw melt output, they do not significantly contribute to the high rate of melting observed in the extruder. Additionally, these lower melt films may affect the stability of the extrusion process and need to be considered in the development of an extrusion model.

Returning to the physical description of the melting system depicted in Fig. 6, the high rate of melting observed in extruders is generated in the upper melt film. As the solid material melts against the barrel, a stationary melt film is formed, moving at the velocity of the barrel. As the melt exits the edge of the solid bed, a fraction of the melt film is dragged along by the relative motion of the barrel. However, not all of the melt film can be dragged out due to the velocity variation across the melt film at the trailing edge of the solid as it enters the melt pool. This velocity profile ultimately determines the melting rate. Various melting models have been developed to determine this thin film velocity profile and calculate the melting rate based on it.

Once the melt film is dragged out from under the solid, the screw flight scrapes the melt film from the barrel and forces it down along the screw flight towards the screw root. At the screw root, the melt is compelled to move toward the solid, which forces it up towards the barrel, where it meets the melt film exiting the solid bed. This constrained motion creates the circulating melt pool shown in Fig. 6. It is the motion of the screw flight that drives the circulating flow in the melt pool and pressurizes the melt.

This melt pressure pushes the solid material against the trailing screw flight, maintaining the observed melting mechanism and minimizing the growth of the melt films between the solid bed and the screw surface.

In the mathematical analysis of the melting system, the mass balance around the melting system (Fig. 17) demonstrates that the amount of melt dragged from under the solid and left on the barrel must be equal to the rate at which solid material is melted. In Fig. 17, we observe that at steady state, the solid moves in the y-direction towards the barrel surface at a velocity V_{sy}, while the melt is dragged away by the barrel. The melting rate is denoted as Ω and is measured in units of mass per time per area (e.g., lbs/h/in^2 or kg/h/cm^2).

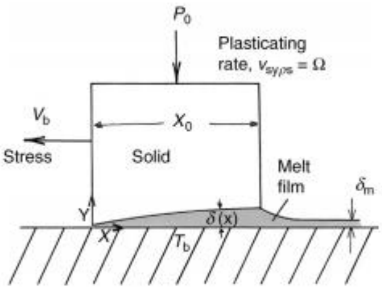


Figure 16: Mass balance around melting solid plug at the barrel surface [1].

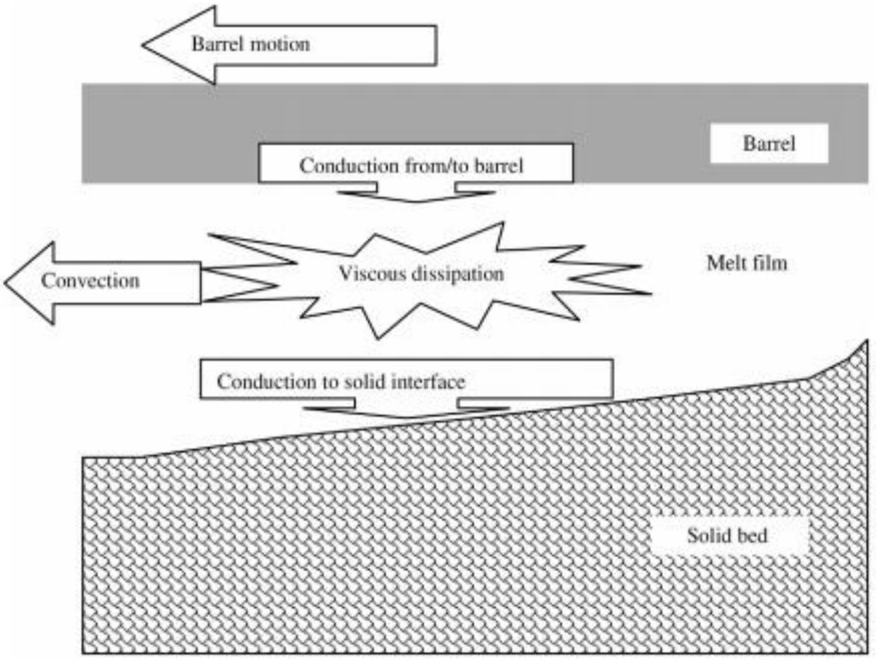


Figure 17: Energy balance in melt film of polymer melting by sliding on a hot barrel surface [1].

2.5.8 Metering Mechanism

The metering section of a single-screw extruder serves as a pump to transport molten polymer out of the screw and through the rest of the melt system. The extruder head pressure refers to the pressure that the extruder screw must generate to push the melt through the breaker plate, transition section, adapter, and die. When the breaker plate, screens, and die are attached to the extruder, the quantity of material forced through the die openings, along with the viscoelastic properties of the resin at the specific melt temperature, determines the amount of pressure that resists the flow.

Typically, the metering section of the extruder features a constant-depth single spiral helix, as shown in Fig. 12.14. The flow pattern of the polymer in this section is complex, with some material following the spiral path of the screw flight directly, while other material traces out a helical path as it moves along the screw channel (Fig. 12.19). This complexity arises due to the combination of drag flow and pressure flow, which are the two driving forces for flow in the metering section.

To understand the flow behaviour, imagine that the screw is stationary, and pressure is applied to the melt at the inlet of the screw channel, forcing the polymer to flow towards the end of the extruder. This corresponds to pressure flow for melt in a rectangular duct. Now, consider the scenario where the screw is stationary, but the barrel is rotating around it. The melt that comes into contact with the barrel will be dragged along by the rotating barrel towards the screw flight. If there is no clearance between the screw flight and the barrel wall, the melt will be scraped off the barrel and pushed down the screw flight until it reaches the screw root. At the screw root, it will be compelled to flow across the screw flight towards the opposing flight.

Upon reaching the opposing screw flight, the melt will be forced upward towards the barrel surface. Once it reaches the barrel surface, it will be moved towards the scraping screw flight by a new section of the barrel, initiating the process again, but slightly further down the barrel (Fig. 12.19). Furthermore, the material in contact with the barrel also drags the fluid below it due to the momentum transfer from the barrel to the melt. This relative motion between the barrel and the screw creates flow across the screw channel, known as drag flow. The drag flow mechanism enables the screw to generate pressure and move the fluid through the screw, even when there are flow restrictions such as a die.

When analysing the flow within the screw, it is customary to combine the effects of drag flow and pressure flow to obtain a combined flow model for the metering section. Similar to the melting calculations, the output of the metering section is determined by integrating the velocity profile of the melt at the end of the screw channel. The goal of theoretical analysis is to derive expressions that describe the output so that it can be estimated accurately [1].

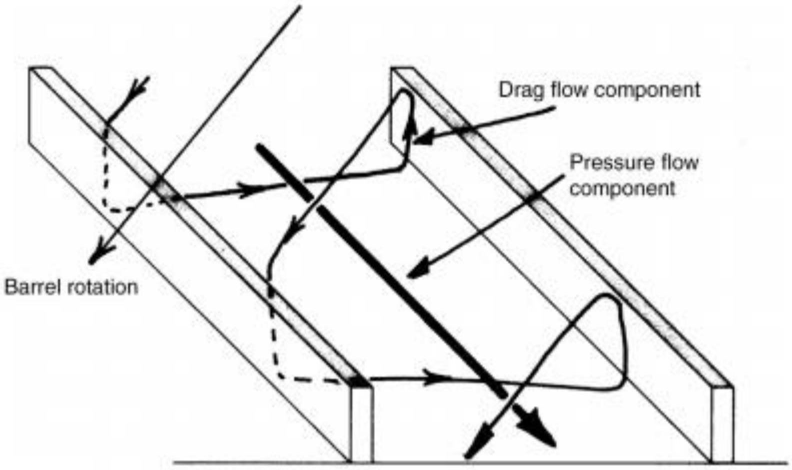


Figure 18: Circulating flow of melt in metering section [1]

Fig. 12.20 shows the geometry of a typical metering section of a single-screw extruder and shows the typical screw dimensions [1].

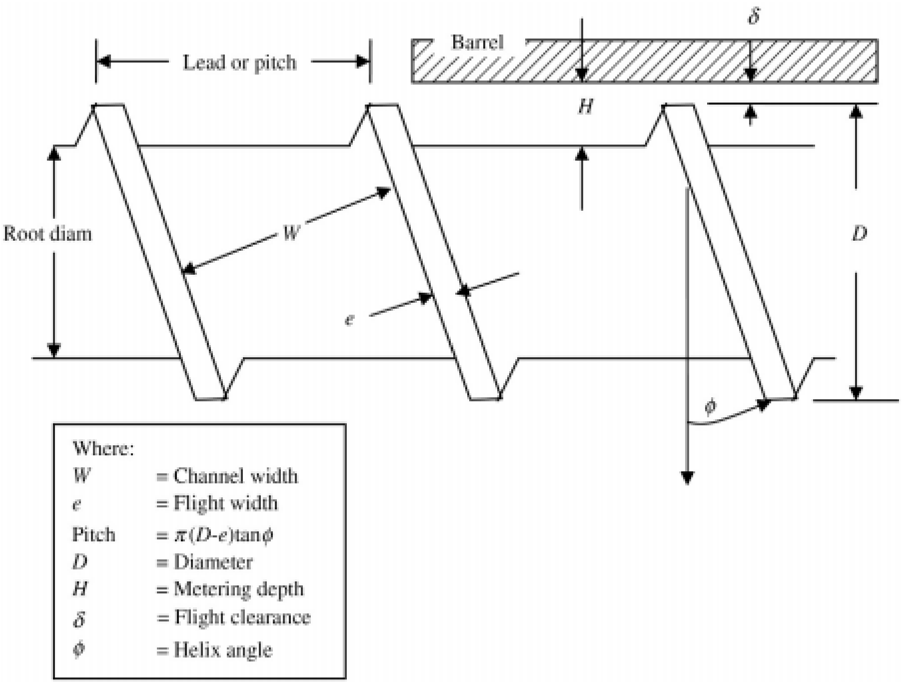


Figure 19: Geometry of typical metering screw [1].

2.5.9 Cooling Mechanism

In the world of 3D printing filament extrusion, the cooling system plays a crucial role in maintaining the quality of the printed output. Utilizing a series of fans strategically positioned along the filament's path, the cooling system effectively dissipates the heat generated during the extrusion process.

As the molten filament emerges from the nozzle, it encounters the first set of fans positioned near the nozzle itself. These fans quickly direct a stream of cool air onto the filament, rapidly reducing its temperature and solidifying its shape. This initial burst of cooling helps prevent any distortion or warping that may occur if the filament remains too hot for an extended period.

Moving along the filament's trajectory, additional fans come into play. Their steady airflow continues to cool the filament, ensuring that it solidifies completely before it has a chance to deform. This consistent cooling process contributes to maintaining dimensional accuracy and overall print quality.

To optimize the cooling process, the cooling system is typically equipped with a control mechanism. This mechanism monitors various parameters, such as extrusion speed and temperature, and adjusts the fan speed accordingly. This adaptive control mechanism ensures that the cooling system operates at its most efficient level, striking the right balance between cooling effectiveness and extrusion speed.

The importance of the cooling system extends beyond the immediate extrusion process. In the realm of filament production and recycling, it plays a vital role in ensuring the quality and consistency of the filament. By rapidly cooling the extruded filament, the system promotes uniformity and minimizes the risk of defects or inconsistencies.

Whether it's producing fresh filaments or recycling used ones, the cooling system proves indispensable in maintaining the integrity and functionality of 3D printing filaments. Its diligent work, aided by the airflow generated by the fans, ensures that the filaments are ready to be transformed into intricate, three-dimensional creations.

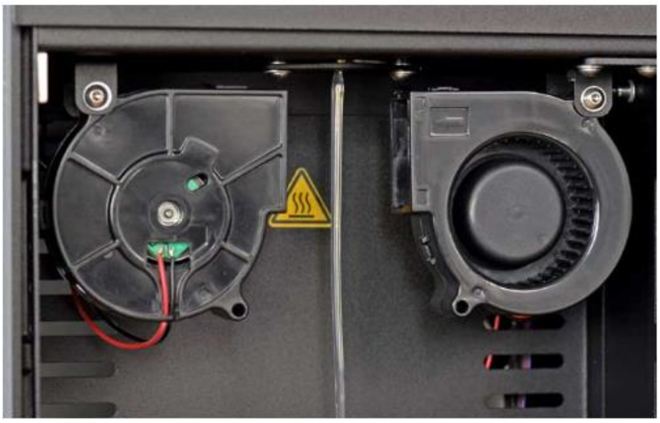


Figure 20: Dual Fan Cooling System for even air distribution [5]

2.5.10 Extrusion Die

At the heart of the 3D printing filament extruder system lies a remarkable component known as the extrusion die or nozzle. This intricate device is responsible for shaping the molten material as it emerges from the barrel, imparting form and structure to the filament. Let us delve into the fascinating functioning of the extrusion die, where precision and ingenuity converge.

As the molten material journeys through the barrel of the extruder, it reaches the critical juncture where it encounters the extrusion die. The die acts as a gateway, where the fluidity of the molten material transforms into a defined and controlled flow. The die consists of a small opening, meticulously crafted to provide the desired shape and dimensions to the emerging filament.

The molten material, under pressure from the extruder, passes through the narrow orifice of the die. This constriction forces the material to take on the shape of the die's profile. The die's design can vary, ranging from circular orifices for cylindrical filaments to more complex geometries for specialized filament shapes.

The precision of the extrusion die is paramount in ensuring the dimensional accuracy and consistency of the filament. Every minute detail of the die's profile and geometry is carefully engineered to impart the desired characteristics to the filament. Whether it is the diameter, cross-sectional shape, or surface texture, the die plays a crucial role in defining the final filament's properties.

To further enhance the functionality of the extrusion die, additional features may be incorporated. For instance, cooling channels can be integrated into the die to accelerate the solidification process of the molten material as it exits the orifice. This aids in maintaining the filament's shape and preventing deformation or sagging.

The extrusion die is not a static component but a dynamic player in the filament extrusion process. It works in concert with other elements, such as the cooling system, to achieve optimal results. By carefully controlling the temperature, pressure, and flow rate, the die ensures a consistent and uniform filament extrusion.

In the realm of filament recycling, the extrusion die becomes a crucial instrument in transforming used materials into a fresh filament. Through the die's careful shaping, the recycled material undergoes a metamorphosis, emerging as a rejuvenated filament ready for a new creative endeavour.

In summary, the extrusion die or nozzle is the artist's brush in the realm of 3D printing filament production and recycling. With its precision and craftsmanship, it imparts shape, structure, and identity to the molten material, transforming it into a tangible filament with unique properties. From cylindrical forms to intricate geometries, the extrusion die's prowess ensures that the filament extruder system continues to breathe life into the boundless world of 3D printing.

Figure 21: Extrusion Nozzles.

2.5.11 Diameter Measuring Device

The diameter of the filament coming from the extruder device will be checked and the tolerances will be monitored to ensure quality of the output. It is usually controlled by micro- controller system (Arduino).

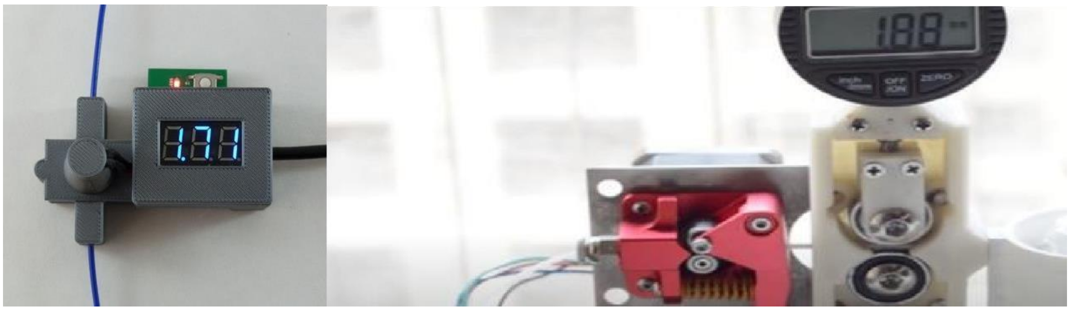


Figure 22: Diameter Measuring Devices.

2.5.12 Spooling

Controlling the spooler speed is important to assure the filament being extruded does not stretch or deform from the tension as it is being spooled. It is controlled by micro- controller system (Arduino).

Figure 23: Spooling Mechanism

Chapter 3

CAD Design

Creating 3D CAD models of 3D filament extruder components using SolidWorks is performed using the following methodology:

1. **Gather design specifications:** Start by gathering the design specifications and requirements for the extruder components. This includes dimensions, tolerances, functionality, and any other relevant details.

2. **Choose CAD software:** Select suitable CAD software that allows you to create 3D models. Popular options include SolidWorks, Autodesk Inventor, Fusion 360, or similar software based on your familiarity and requirements.

3. **Create a new project:** Open the CAD software and create a new project or file to begin the modeling process.

4. **Set units and coordinate system:** Set the appropriate units (e.g., millimeters, inches) and coordinate system according to the design specifications.

5. **Create basic shapes:** Start by creating basic shapes that form the foundation of the extruder components. This can include cylinders, boxes, spheres, or any other geometric primitives.

6. **Use sketching tools:** Utilize the sketching tools provided by the CAD software to define 2D profiles of the components. Sketches can be created on different planes and then extruded, revolved, or lofted to form the desired 3D shapes.

7. **Apply dimensions and constraints:** Apply accurate dimensions and constraints to the sketches to ensure the components meet the specified requirements. This includes specifying distances, angles, and other geometric relationships.

8. **Add features:** Use the CAD software's feature tools to add more complex features to the components. This can involve creating holes, fillets, chamfers, threads, or any other necessary features.

9. **Create assemblies:** If your extruder has multiple components, create separate 3D models for each component and then assemble them together using assembly tools provided by the CAD software. Ensure proper alignment and fit between the components.

10. **Validate and refine:** Regularly review and validate the 3D models against the design specifications. Make any necessary adjustments or refinements to ensure accuracy and functionality.

11. **Apply materials and textures:** Assign appropriate materials and textures to the 3D models to enhance the visual representation. This step is optional but can provide a more realistic and informative representation of the extruder components.

12. **Generate technical drawings:** Generate detailed technical drawings of the extruder components, including orthographic views, dimensions, tolerances, and any other necessary annotations. These drawings are useful for manufacturing and assembly purposes.

13. **Save and export:** Save the CAD files in the appropriate formats supported by the CAD software. Additionally, export the models in commonly used formats such as STL or STEP for compatibility with other software or 3D printing processes.

It's important to note that this methodology may vary depending on the specific CAD software being used and the complexity of the extruder components. Familiarity with the chosen CAD software and experience in 3D modeling will significantly aid in efficiently creating accurate and functional 3D CAD models.

3.1 Hopper:

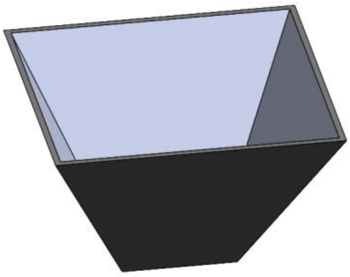


Figure 24: Hopper

3.2 Barrel with Hopper:

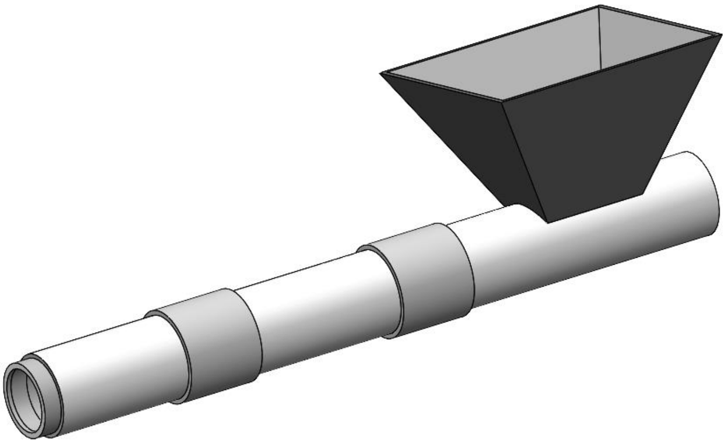


Figure 25: Barrel with Hopper

3.3 Barrel with Band Heaters:

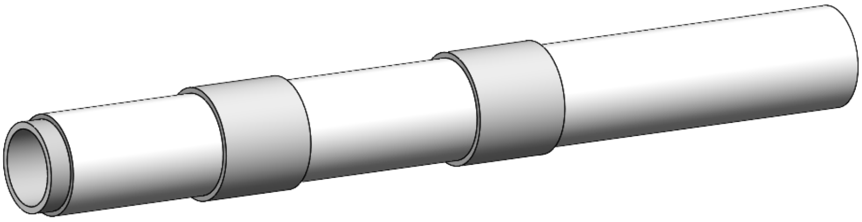


Figure 26: Barrel with heaters

3.4 Lead Screw:

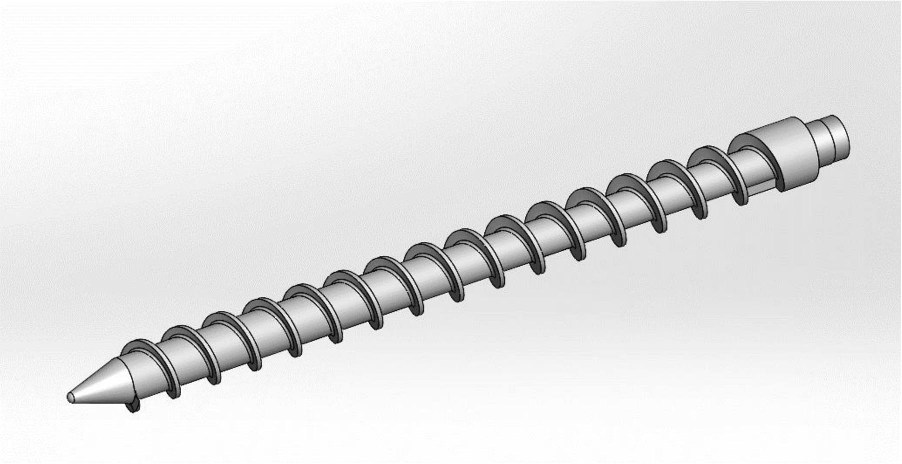


Figure 27: Lead Screw

3.5 Sew Eurodrive Motor:

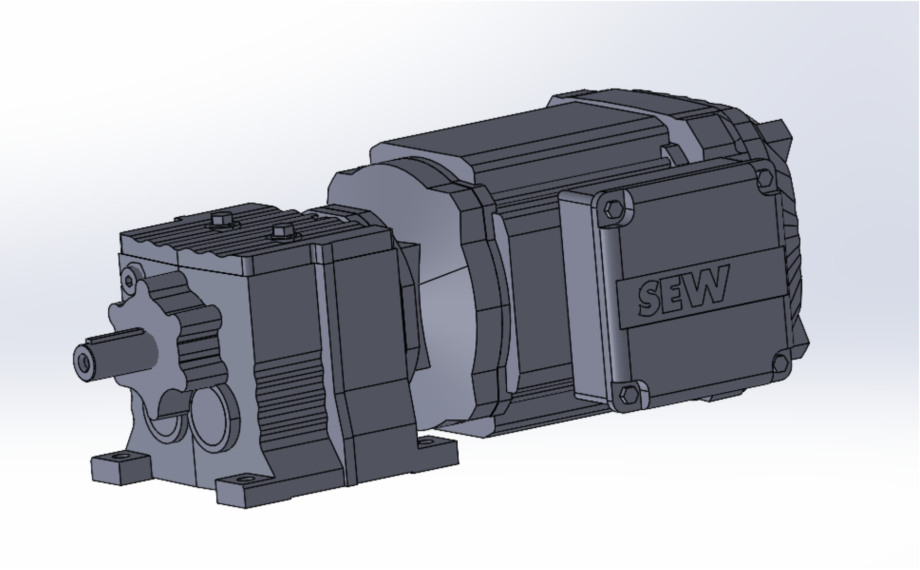


Figure 28: Sew Eurodrive Motor

3.6 Coupling:

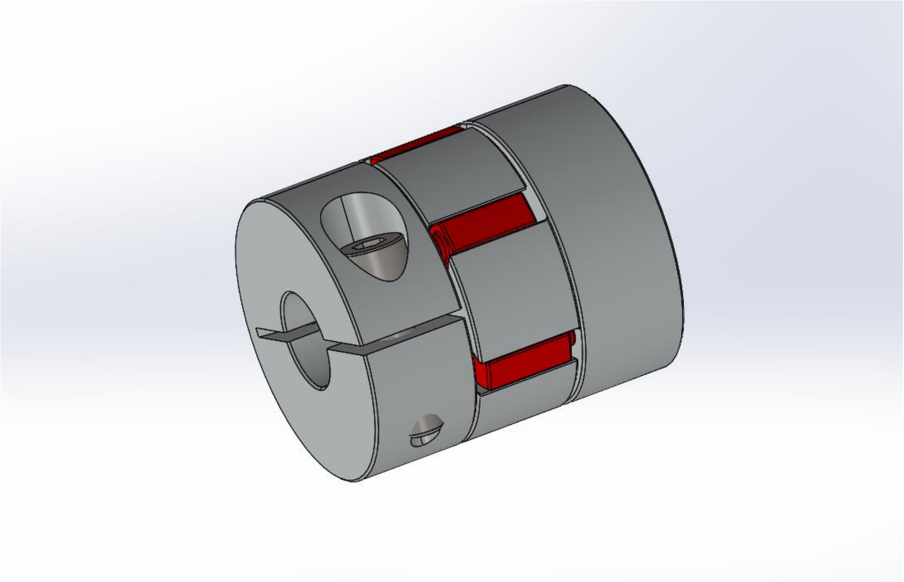


Figure 29: Jaw Coupling

3.7 Nozzle:

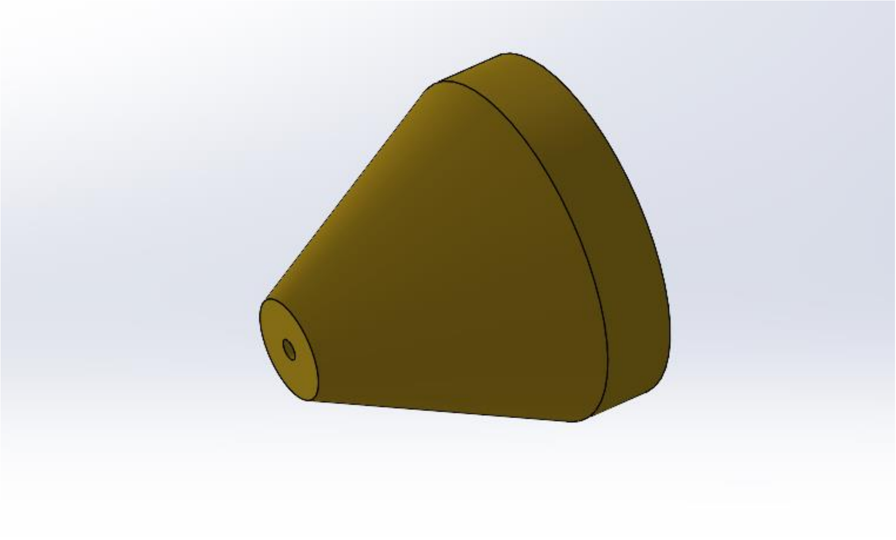


Figure 30: Nozzle

3.8 Stand (Bench Support):

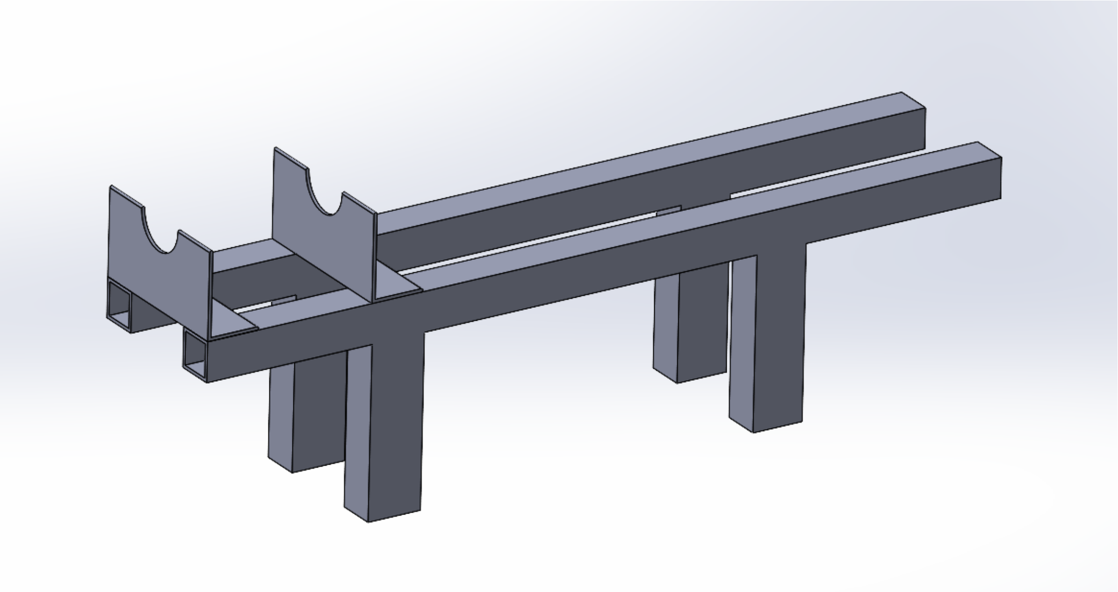


Figure 31: Stand

3.9 Extruder System (Assembled):

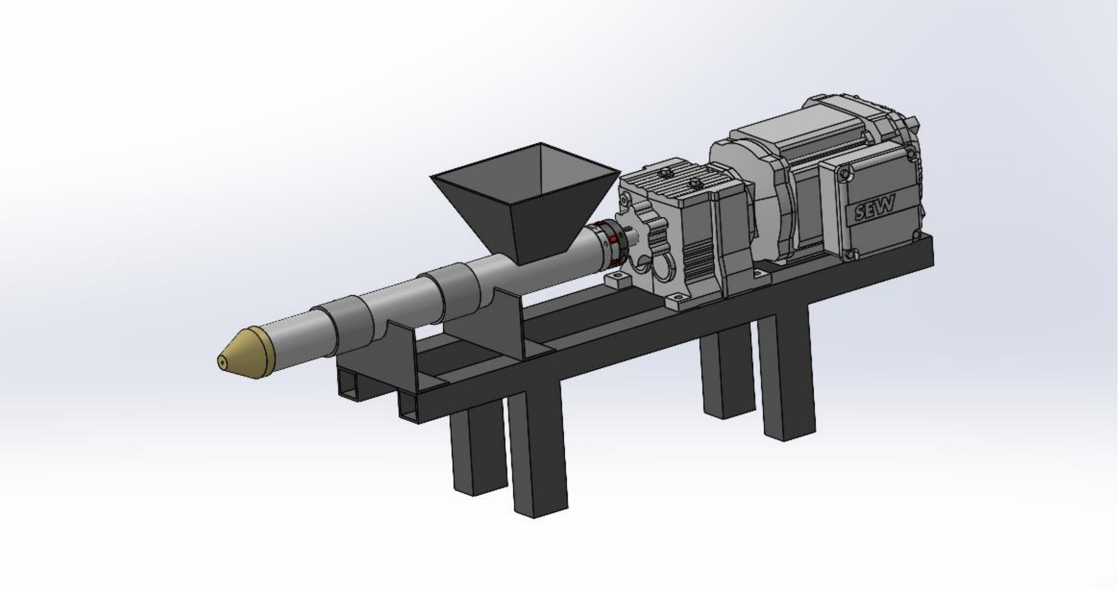


Figure 32: Extruder System (Assembled)

Chapter 4

Thermal Analysis

Performing thermal analysis on a lead screw inside the barrel with two heaters for a filament extruder system is performed by using following methodology:

1. **Define the analysis objectives:** Clearly define the goals of the thermal analysis, such as determining the temperature distribution along the lead screw, identifying potential hotspots, evaluating the effectiveness of the heaters, or assessing thermal stability.

2. **Gather system information:** Collect relevant information about the filament extruder system, including the dimensions and material properties of the lead screw, the position and specifications of the heaters, the surrounding environment, and any other factors that may impact the thermal behavior.

3. **Create a 3D CAD model:** Develop a 3D CAD model of the entire filament extruder system, including the barrel, lead screw, heaters, and any other relevant components. Ensure accurate representation of dimensions and geometry.

4. **Define material properties:** Assign appropriate material properties to each component, such as thermal conductivity, specific heat capacity, and thermal expansion coefficient. These properties should reflect the actual materials used in the system.

5. **Apply boundary conditions:** Specify the boundary conditions for the analysis. This includes setting the temperature and heat transfer coefficients at the barrel's external surfaces, defining the temperature at the heaters, and considering any other relevant thermal interactions with the surroundings.

6. **Mesh generation:** Create a mesh on the CAD model to discretize the geometry into smaller elements. The mesh should be fine enough to capture the temperature gradients accurately while maintaining reasonable computational requirements.

7. **Select a thermal analysis method:** Choose a suitable thermal analysis method based on the complexity and objectives of the analysis. Common methods include finite element analysis (FEA) or computational fluid dynamics (CFD) simulations. FEA is generally

suitable for steady-state or transient heat conduction problems, while CFD can be used for analyzing convective heat transfer.

8. **Define the analysis parameters:** Specify the analysis parameters, such as the time step for transient analysis or the maximum temperature for steady-state analysis. Set appropriate convergence criteria to ensure accurate results.

9. **Run the analysis:** Execute the thermal analysis using the selected method and software. Monitor the progress and convergence of the analysis to ensure reliable results.

10. **Analyze the results:** Once the analysis is complete, analyze the obtained temperature distribution along the lead screw and other relevant outputs. Identify areas of concern, such as excessive temperatures, temperature gradients, or inadequate heating.

11. **Optimize the system:** Based on the analysis results, make necessary design modifications to optimize the thermal performance of the filament extruder system. This may involve adjusting the position or power of the heaters, improving heat transfer mechanisms, or incorporating additional cooling methods.

12. **Validate the results:** Validate the analysis results by comparing them with experimental data or theoretical calculations if available. This step helps ensure the accuracy and reliability of the thermal analysis.

13. **Iterate if necessary:** If the analysis results do not meet the desired objectives or if further improvements are needed, iterate the analysis by adjusting the parameters, refining the model, or making additional design changes.

14. **Document and report:** Document the analysis methodology, assumptions, and results. Prepare a detailed report summarizing the thermal analysis process, findings, and any recommendations for design improvements.

Performing thermal analysis on a lead screw inside a barrel with heaters requires proficiency in thermal simulation software, knowledge of heat transfer principles, and a solid understanding of the filament extruder system.

4.1 Thermal Analysis on Barrel Only:

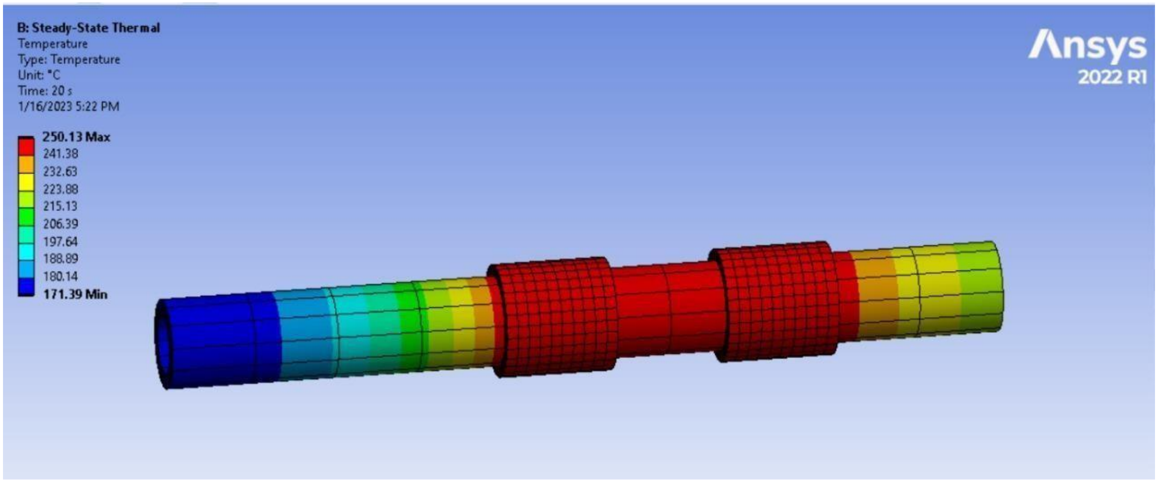


Figure 33: Steady state heat analysis on barrel only

4.2 Thermal Analysis on Barrel with Lead screw inside:

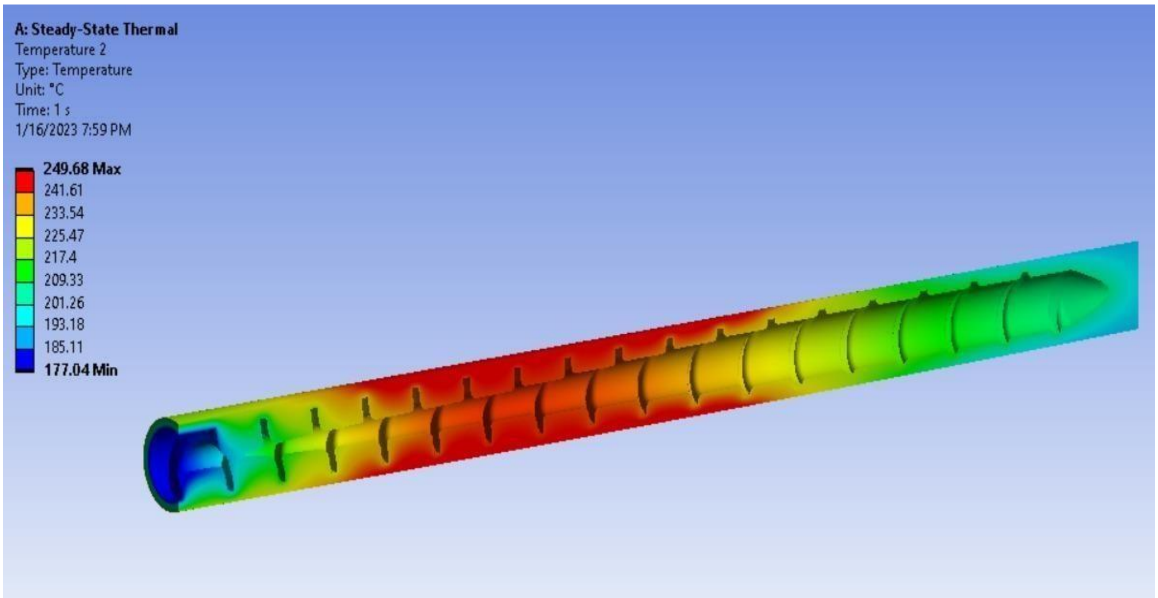


Figure 34: Steady state heat analysis on barrel with lead screw inside

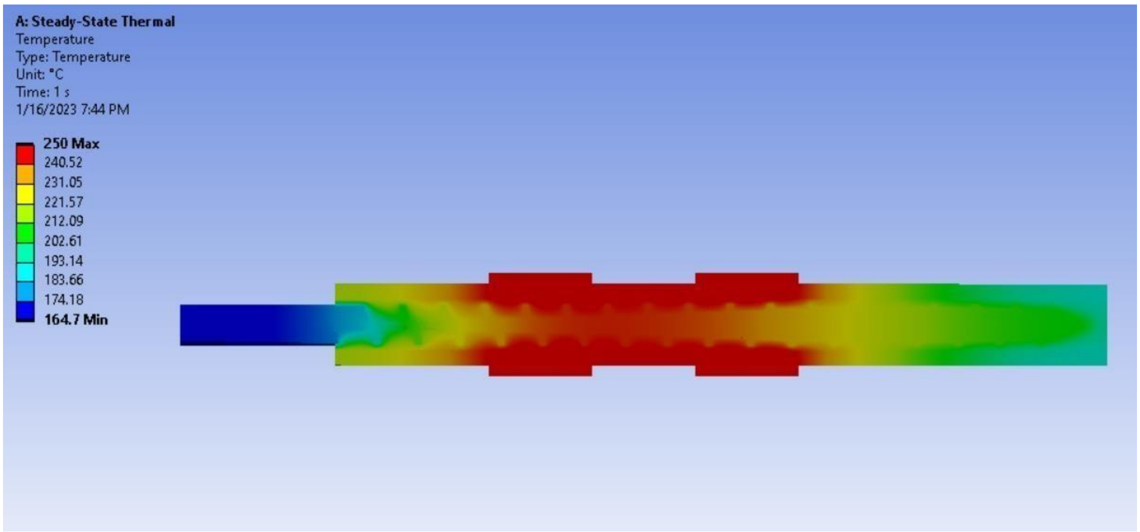


Figure 35: Steady state heat analysis on lead screw inside barrel (Sectioned View)

4.3 Thermal Analysis on Barrel with Lead screw and Material inside:

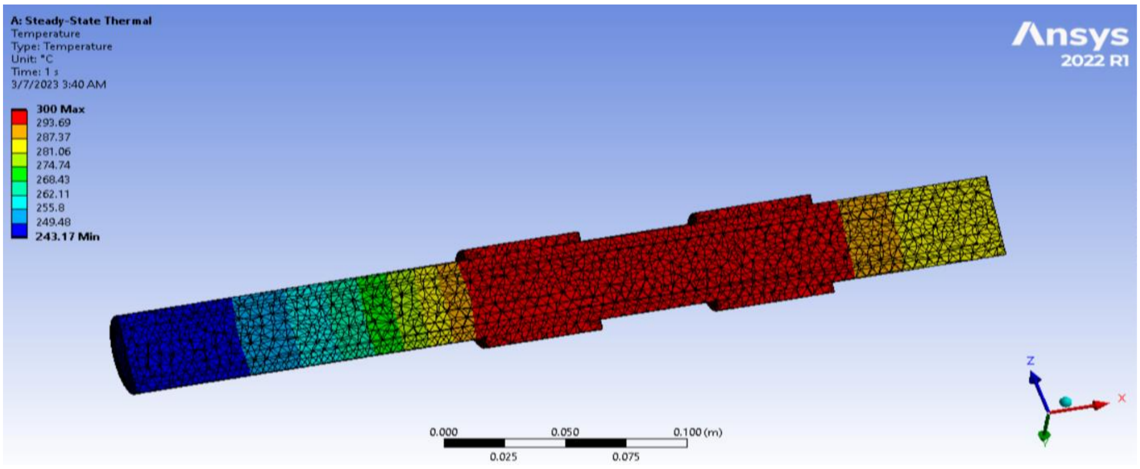


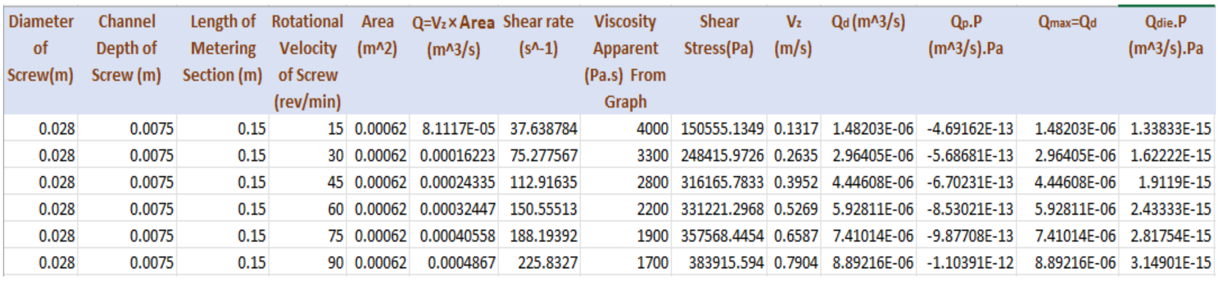
Figure 36: Steady state heat analysis on barrel with lead screw and material inside.

Chapter 5

Power/Torque Calculations

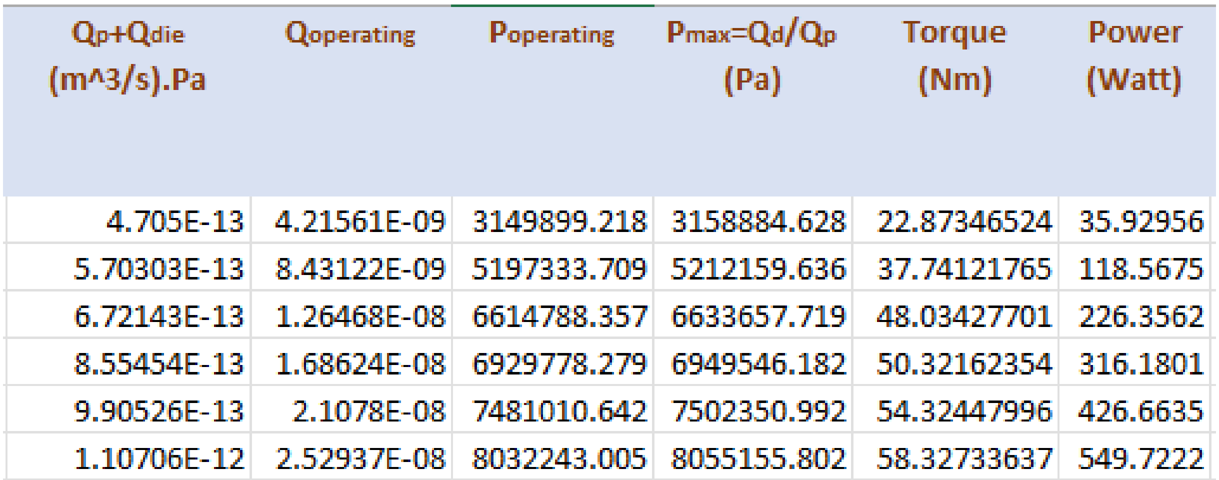
5.1 Calculations:

The calculations are performed on Microsoft Excel by using equations mentioned in Appendix-Equations Used.



Diameter of Screw(m)	Channel Depth of Screw (m)	Length of Metering Section (m)	Rotational Velocity of Screw (rev/min)	Area (m^2)	$Q=V_z\times$ **Area** (m^3/s)	Shear rate (s^-1)	Viscosity Apparent (Pa.s) From Graph	Shear Stress(Pa)	V_z (m/s)	Q_d (m^3/s)	$Q_p.P$ (m^3/s).Pa	$Q_{max}=Q_d$	$Q_{die}.P$ (m^3/s).Pa
0.028	0.0075	0.15	15	0.00062	8.1117E-05	37.638784	4000	150555.1349	0.1317	1.48203E-06	-4.69162E-13	1.48203E-06	1.33833E-15
0.028	0.0075	0.15	30	0.00062	0.00016223	75.277567	3300	248415.9726	0.2635	2.96405E-06	-5.68681E-13	2.96405E-06	1.62222E-15
0.028	0.0075	0.15	45	0.00062	0.00024335	112.91635	2800	316165.7833	0.3952	4.44608E-06	-6.70231E-13	4.44608E-06	1.9119E-15
0.028	0.0075	0.15	60	0.00062	0.00032447	150.55513	2200	331221.2968	0.5269	5.92811E-06	-8.53021E-13	5.92811E-06	2.43333E-15
0.028	0.0075	0.15	75	0.00062	0.00040558	188.19392	1900	357568.4454	0.6587	7.41014E-06	-9.87708E-13	7.41014E-06	2.81754E-15
0.028	0.0075	0.15	90	0.00062	0.0004867	225.8327	1700	383915.594	0.7904	8.89216E-06	-1.10391E-12	8.89216E-06	3.14901E-15

Table 1: Shear Stress Calculation Table for Motor



Q_p+Q_{die} (m^3/s).Pa	$Q_{operating}$	$P_{operating}$	$P_{max}=Q_d/Q_p$ (Pa)	Torque (Nm)	Power (Watt)
4.705E-13	4.21561E-09	3149899.218	3158884.628	22.87346524	35.92956
5.70303E-13	8.43122E-09	5197333.709	5212159.636	37.74121765	118.5675
6.72143E-13	1.26468E-08	6614788.357	6633657.719	48.03427701	226.3562
8.55454E-13	1.68624E-08	6929778.279	6949546.182	50.32162354	316.1801
9.90526E-13	2.1078E-08	7481010.642	7502350.992	54.32447996	426.6635
1.10706E-12	2.52937E-08	8032243.005	8055155.802	58.32733637	549.7222

Table 2: Torque/Power Calculation Table for Motor

Chapter 6

Temperature Controller

6.1 Description:

A temperature controller using Arduino is a practical and cost-effective solution for regulating the temperature of various systems and processes. It finds applications in areas such as greenhouse temperature control, fermentation chambers for brewing beer or making yogurt, and more. By utilizing an Arduino board, along with basic electronic components like a temperature sensor and a relay or solid-state switch, you can easily build a temperature controller that meets your specific requirements.

The Arduino platform offers the advantage of easy programming, as it uses a language based on C++ that is widely accessible and supported by a large online community. With readily available libraries and code examples, you can quickly get started with your temperature controller project and customize it as needed.

Flexibility is another benefit of using an Arduino-based temperature controller. You can modify the code to adjust temperature setpoints, incorporate additional sensors or actuators, and even add features like user interfaces or data logging. This adaptability makes it ideal for prototyping and experimentation in various temperature control applications.

To begin building your own temperature controller with Arduino, you can find abundant resources online, including tutorials, code examples, and forums. Arduino also offers a range of compatible sensors and modules, simplifying the process of creating a comprehensive temperature control system.

Whether you are a hobbyist, a student, or a professional, an Arduino-based temperature controller provides a practical and flexible solution for regulating the temperature of your systems or processes, without breaking the bank.

We built a temperature controller using Arduino and several other electronic components but the only drawback it had was that it was not compact and had safety issues. Therefore, we decided to procure temperature controllers from the manufacturer as shown in Fig 33.

LED Digital Temperature Controller E5EN-YR40K has temperature range of 0-399 °C and wattage of 150 Watts.

Figure 37: LED Digital Temperature Controller E5EN-YR40K

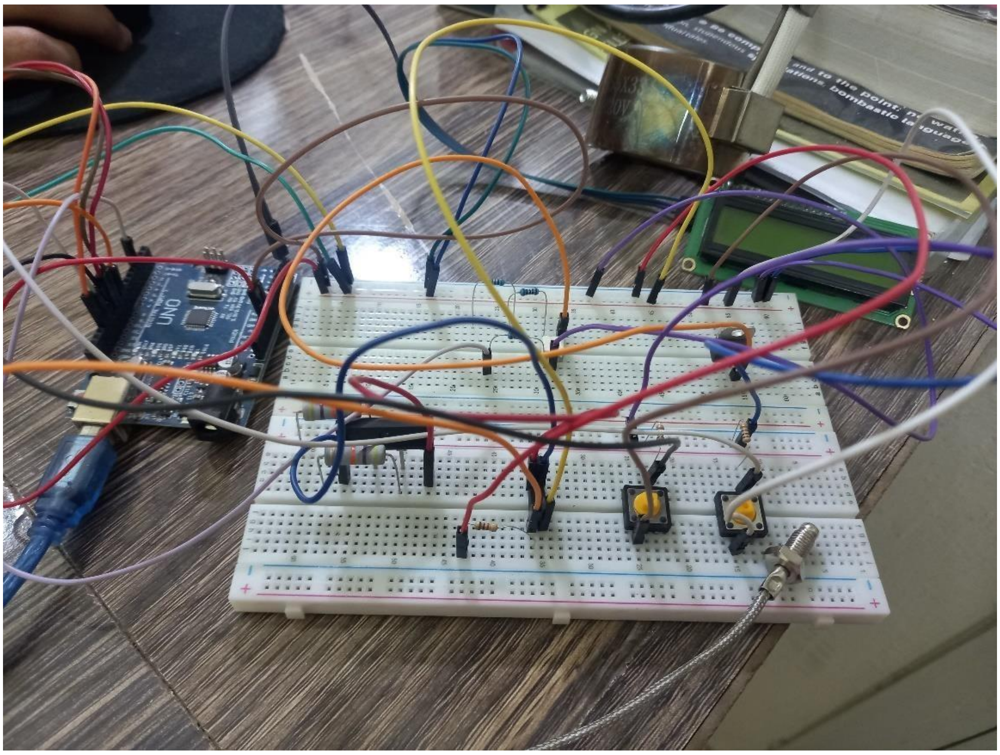


Figure 38: Temperature Controller Circuit made using Arduino.

Chapter 7

Motor Controller

7.1 Description:

The world of motor control is revolutionized by the variable frequency drive (VFD) motor controller, a remarkable device designed to regulate the speed of three-phase AC motors. This innovative technology offers precise control, energy efficiency, and enhanced performance in a wide range of industrial applications. Let's delve into the introduction and working of this powerful motor controller.

The variable frequency drive motor controller serves as the intermediary between the power source and the motor, enabling seamless control over the motor's rotational speed. Its primary function is to vary the frequency and voltage supplied to the motor, thereby adjusting the motor's speed to meet the specific requirements of the application.

The VFD motor controller operates on the principle of pulse-width modulation (PWM). It takes the incoming AC power supply, typically three-phase, and converts it into DC power using a rectifier circuit. The rectified DC power is then passed through a DC link capacitor, which smooths out any voltage fluctuations.

To achieve variable speed control, the VFD motor controller utilizes insulated gate bipolar transistors (IGBTs) or metal-oxide-semiconductor field-effect transistors (MOSFETs) to convert the DC power back into AC power of adjustable frequency and voltage. By adjusting the frequency and voltage output, the VFD motor controller can precisely control the rotational speed of the motor.

The speed control is achieved through the manipulation of the motor's operating frequency. By increasing or decreasing the frequency supplied to the motor, the VFD motor controller can accelerate or decelerate the motor's speed. This allows for fine-tuning of motor performance, ensuring optimal operation in different load conditions.

In addition to speed control, the VFD motor controller offers several advantages. It provides soft-start capabilities, gradually ramping up the motor's speed to reduce mechanical stress and electrical surges. It also allows for precise torque control, enabling efficient operation and precise positioning in applications that require high accuracy.

Furthermore, the VFD motor controller enhances energy efficiency by matching the motor's speed with the load requirements. By adjusting the motor speed to match the demands of the application, energy consumption is optimized, resulting in significant energy savings.

The VFD motor controller also provides additional features such as motor protection mechanisms, fault diagnostics, and communication interfaces for integration with control systems.

In summary, the variable frequency drive motor controller is a vital component in modern motor control systems. Its ability to regulate the speed of three-phase AC motors with precision, energy efficiency, and advanced features makes it indispensable in a wide range of industrial applications. With its flexible speed control and enhanced performance, the VFD motor controller revolutionizes motor-driven processes, offering greater control, reliability, and energy savings.

We procured a motor controller by SEW EURODRIVE the same manufacturer we procured the motor from.

Sew Eurodrive RX57/A Motor Controller has operating voltage range of 220-240 V and frequency range of 50-60 Hz.

Figure 39: Sew Eurodrive RX57/A Motor Controller

Chapter 8

Motor

8.1 Description:

The 550-Watt 3-phase AC motor manufactured by Sew Euro Drive is a reliable and high-performance motor specifically designed to meet the demanding requirements of various industrial and automation applications. As part of the modular DR motor system, this motor offers customization options and seamless integration with other motor components, ensuring flexibility and compatibility.

One notable feature of the 550-Watt motor is its impressive efficiency. With an efficiency rating of up to 85%, it significantly reduces energy consumption, leading to cost savings and environmental benefits. This efficiency is particularly valuable in applications where motors are utilized extensively, as it can result in substantial long-term cost reductions.

Despite its exceptional performance, the 550-Watt motor maintains a compact and space-saving design. Its small footprint allows for easy integration into a wide range of machinery and equipment, making it an ideal choice for applications where limited space is a consideration.

Maintenance and serviceability are crucial aspects of any motor, and the 550-Watt motor excels in these areas. Its modular design facilitates quick and hassle-free replacement or repair of individual components, minimizing downtime and reducing repair costs. This feature ensures that the motor operates reliably and remains readily available for optimal productivity.

The Sew Euro Drive 550-Watt motor is designed and tested to meet stringent international safety and quality standards, including IEC, EN, UL, and CSA certifications. This dedication to quality guarantees that the motor operates safely and reliably, even in demanding and challenging applications.

Moreover, the motor is engineered for seamless integration with other motor components like gearboxes and controllers. This level of compatibility enables greater customization and adaptability, allowing users to create tailored motor solutions that precisely meet their specific application requirements.

When selecting a motor, it is essential to consider factors such as application demands, power and torque requirements, and the level of control and customization needed. With its exceptional efficiency, compact design, easy maintenance, and serviceability, the 550 Watt 3-phase AC motor by Sew Euro Drive emerges as a superior choice for a diverse range of industrial and automation applications.

In conclusion, the 550-Watt 3-phase AC motor manufactured by Sew Euro Drive stands as a high-performance motor offering a comprehensive array of features and benefits. Its modular design, coupled with outstanding efficiency, easy maintenance, and serviceability, make it a reliable and versatile option for applications where performance, reliability, and energy efficiency are of utmost importance.

Sew Eurodrive R17DRN80MK4 550W AC Induction Gearmotor has maximum torque of 69 Nm, Gear ratio of 2:1 and RPM range of 0-1366 RPM.

Figure 40: SEW EURODRIVE R17DRN80MK4 550W AC Induction Gearmotor

Chapter 9

Extrusion Barrel

9.1 Description:

An extrusion barrel crafted from high-pressure carbon steel, specifically **ASTM A516 Grade 70** having **OD = 52 mm**, **ID = 40.5 mm,** and **thickness = 12 mm** stands as a vital component within the realm of extrusion machinery deployed in the plastics industry. The selection of this steel variant arises from its commendable attributes, including exceptional strength, superb toughness, and formidable corrosion resistance.

High-pressure carbon steel proves its mettle by effectively enduring the intense temperatures and pressures generated during the extrusion process. The steel's remarkable resistance allows it to withstand temperatures soaring up to 450°C, making it an ideal candidate for various extrusion applications.

Beyond its thermal resilience, high-pressure carbon steel exhibits a remarkable resistance to deformation and cracking. The steel's inherent toughness equips it to withstand the demanding stresses and strains encountered throughout the extrusion process, ensuring prolonged operational efficiency.

Another remarkable facet of high-pressure carbon steel is its impressive corrosion resistance, contributing to the longevity of the extrusion barrel and minimizing maintenance demands. This attribute proves particularly valuable in scenarios where the extrusion machine experiences frequent usage, culminating in significant cost savings over time.

To guarantee the highest calibre and performance of the extrusion barrel, it is imperative to collaborate with reputable manufacturers well-versed in the production of high-pressure carbon steel extrusion barrels. A reliable manufacturer should offer comprehensive documentation and testing results to validate the quality and performance of their extrusion barrels.

Selecting an extrusion barrel forged from high-pressure carbon steel demands careful consideration of factors such as the specific requirements of the application, the dimensions and capacity of the extrusion machine, and the desired level of control and customization. Such meticulous evaluation ensures that the extrusion barrel aligns precisely with the application's unique needs, enabling steadfast performance even under the most demanding circumstances.

In addition to its commendable strength and toughness, high-pressure carbon steel boasts exceptional ductility, facilitating ease of forming and shaping during the manufacturing process. This flexibility renders it a versatile choice for a wide spectrum of extrusion applications.

The durability of high-pressure carbon steel serves as another prominent feature, amplifying the lifespan of the extrusion barrel while diminishing maintenance requirements. This durability stems from the steel's ability to endure the arduous stresses and strains encountered during the extrusion process, coupled with its resistance to corrosion and deformation.

Furthermore, high-pressure carbon steel exhibits remarkable fatigue strength, enabling the extrusion barrel to withstand repeated stresses and strains without succumbing to fatigue or failure. This characteristic ensures consistent and reliable operation of the extrusion machine over prolonged periods.

When assessing the cost-effectiveness of extrusion barrels, high-pressure carbon steel emerges as a wise investment. Although it may initially entail higher expenses compared to alternative materials, its long-term durability and corrosion resistance translate into reduced maintenance and replacement costs.

To guarantee top-notch quality, the production of extrusion barrels necessitates adherence to appropriate manufacturing and quality control processes. This encompasses meticulous raw material selection, precise machining and finishing techniques, and rigorous testing to ensure compliance with all relevant specifications and standards.

When designing an extrusion machine, it becomes imperative to carefully deliberate the specific requirements of the application and select the most fitting extrusion barrel material. High-pressure carbon steel remains a favoured choice due to its outstanding strength, toughness, corrosion resistance, and capability to endure high temperatures and pressures.

Beyond its utilization in extrusion barrels, high-pressure carbon steel finds widespread application in an array of other industrial domains, including pressure vessels, boilers, and pipelines. Its exceptional strength, toughness, and corrosion resistance render it a preferred material choice for these diverse applications as well.

In conclusion, an extrusion barrel fabricated from high-pressure carbon steel, particularly ASTM A516 Grade 70, represents an exceptional choice for the plastics industry. Its impressive strength, toughness, corrosion resistance, and ability to withstand extreme temperatures and pressures make it a versatile and reliable option for a wide range of engineering applications.

Figure 41: Extrusion Barrel

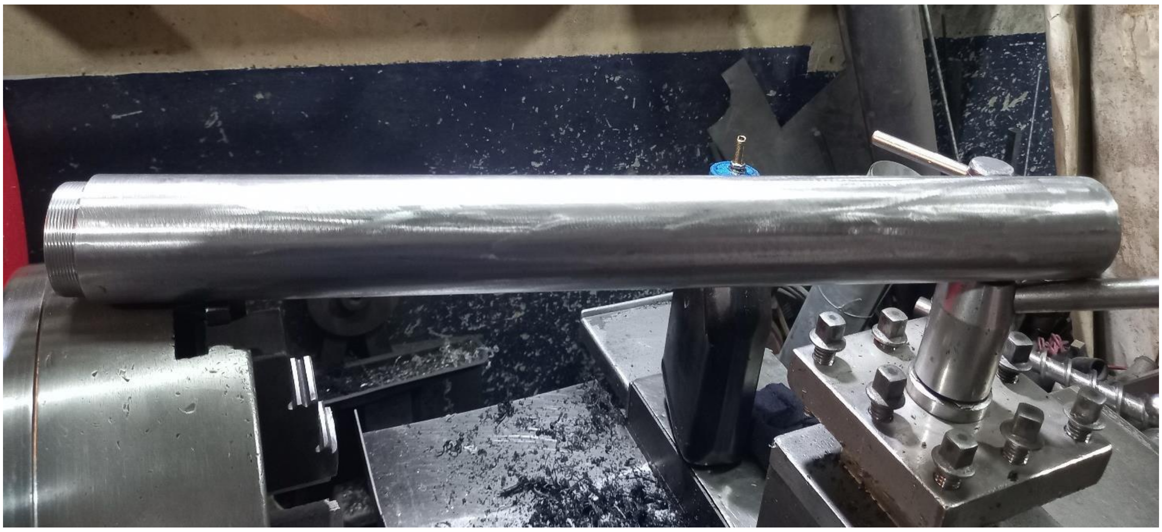


Figure 42: Extrusion Barrel (Manufactured)

Figure 43: Extrusion Barrel (Side View)

Chapter 10

Custom-Designed Lead Screw

10.1 Manufacturing Methodology:

As described earlier in **section 2.5.2,** lead screws come in standard sizes described by their L/D ratios such as 12:1, 16:1, 24:1, etc. We first planned to use a lead screw with L/D ratio of 12:1 but since we had already procured the barrel of length 500 mm because of saving the manufacturing cost, we had to design a lead screw having custom L/D ratio. Designing and fabricating a lead screw with the specified characteristics requires careful planning and consideration. Here's a step-by-step approach we used for designing and fabricating the lead screw:

- **Design Concept:**

  Based on careful observations and literature review, we designed a lead screw with a length of **520 mm,** a root diameter of **28 mm,** pitch of **28 mm,** a compression ratio of **1.5:1,** a helix angle of **17.56°,** a flight thickness of **3 mm,** and specific flight channel depths of **9 mm** and **6 mm** at the feeding and metering zones respectively. Additionally, the lead screw is fabricated using **Mild Steel (AISI 4140).**

- **Calculating the Lead:**

  We calculated the lead, which determined the axial distance traveled by the screw in one complete revolution. The lead was calculated using the formula:

  Lead = (Root Diameter) x (Compression Ratio)

  For our lead screw, the lead was:

  Lead = 28 mm x 1.5 = **42 mm**

- **Determining the Helix Angle:**

  We determined the helix angle, which represented the angle between the helix of the screw and its axis. In this case, the selected helix angle was 17.56 degrees.

- **Designing the Flight:**

  We designed the flight, which was the helical ridge that wrapped around the lead screw. We took into consideration the flight thickness, channel depth at the feeding zone, and channel depth at the metering zone considering the compression ratio.

  Flight Thickness: The flight thickness was specified as 3 mm.

  Channel Depth at Feeding Zone: The channel depth at the feeding zone was specified as 9 mm.

Channel Depth at Metering Zone: The channel depth at the metering zone was specified as 6 mm.

- **Material Selection:**

  Based on the specifications, we chose to fabricate the lead screw using Mild Steel (AISI 4140), a common choice for its mechanical properties and ease of fabrication.

- **Fabrication Process:**

  To fabricate the lead screw, we followed these steps:

  Material Preparation: We obtained a suitable length of mild steel rod with a diameter slightly larger than the root diameter of 28 mm.

  Cutting: We cut the rod to the desired length of 520 mm using a lathe.

  Machining: We used a lathe to carefully machine the rod to achieve the desired root diameter, flight thickness, and helix angle. We placed flight clearance of 0.5 mm between barrel and lead screw. We paid attention to maintaining accurate dimensions and a smooth finish.

  Channel Formation: We utilized suitable cutting tools or milling techniques to create the flight channels at the feeding and metering zones. We ensured that the channel depths aligned with the specified values.

  Finishing: We performed post-machining processes, such as deburring and polishing, to ensure a refined surface finish.

  Throughout the design and fabrication process, we employed precision and attention to detail to achieve a lead screw that met the specified characteristics.

  An extrusion lead screw made of Mild Steel (AISI 4140) with an **L/D ratio = 13:1** is fabricated. This type of lead screw has many advantages over other materials, making it an excellent choice for use in extrusion applications.

  One of the main advantages of using mild steel is that it is a cost-effective material compared to other materials like stainless steel or titanium. This is especially important in high-volume manufacturing environments where cost savings are a priority.

  Mild steel is also known for its high strength, toughness, and durability. This makes it an excellent choice for extrusion lead screws that are subject to high stress and pressure. AISI 4140 is a specific type of mild steel that has good wear resistance, making it ideal for use in applications requiring high strength and toughness.

The L/D ratio of 13:1 for this extrusion lead screw is a relatively high ratio, which means that the length of the screw is 13 times its diameter. This high ratio results in a longer thread length, which allows for more gradual and precise movement of the extruder.

The high strength of mild steel also allows for the use of smaller diameter lead screws without sacrificing performance. This can lead to cost savings as well since smaller diameter screws are less expensive to produce.

The L/D ratio of 13:1 also allows for higher torque capacity and more precise control of the extruder. This is important in applications where precise control of the extruded material is critical to the final product quality.

Mild steel is also easy to machine, which makes it an excellent choice to produce extrusion lead screws. This allows for precise machining of the threads and other features of the screw, which is critical for the proper functioning of the extruder.

Another advantage of using mild steel for extrusion lead screws is its resistance to wear and tear. The high wear resistance of AISI 4140 steel ensures that the lead screw will last a long time, reducing the need for frequent replacements and maintenance.

The L/D ratio of 13:1 is also important for reducing the risk of buckling or bending of the lead screw. This is because a longer screw with a higher L/D ratio has more stability and can withstand higher loads without bending or buckling.

The high strength and toughness of mild steel also make it an excellent choice for extrusion lead screws that are subject to high stress and pressure. This is particularly important in high-speed extrusion applications where the extruder needs to operate at high speeds and pressures.

The L/D ratio of 13:1 is also ideal for achieving the desired level of shear stress on the plastic material being extruded. This is because a longer screw with a higher L/D ratio result in a more gradual increase in shear stress, which is important for producing high-quality extruded products.

The use of mild steel for extrusion lead screws allows for easy customization to meet specific application requirements. This can include modifications to the thread pitch, lead angle, and other features of the screw to optimize performance for the specific extrusion application.

In addition to its durability and wear resistance, mild steel is also a good choice for extrusion lead screws due to its corrosion resistance. This is especially important in applications where the extruder may be exposed to corrosive materials or environments.

The L/D ratio of 13:1 is also important for ensuring proper heat distribution along the length of the lead screw. This is critical for maintaining consistent temperatures throughout the extruder and ensuring that the plastic material is properly melted and extruded.

The high strength and toughness of mild steel also make it an excellent choice for extrusion lead screws that are subject to shock and vibration. This is particularly important in applications where the extruder needs to operate at high speeds.

The L/D ratio of 13:1 is also ideal for achieving the desired level of shear stress on the plastic material being extruded. This is because a longer screw with a higher L/D ratio result in a more gradual increase in shear stress, which is important for producing high-quality extruded products.

Finally, the use of mild steel for extrusion lead screws allows for easy customization to meet specific application requirements. This can include modifications to the thread pitch, lead angle, and other features of the screw to optimize performance for the specific extrusion application.

Figure 44: Extrusion Lead Screw

Figure 45: Extrusion Lead Screw (Manufactured)

Chapter 11

Barrel and Lead Screw System

11.1 Introduction:

Extrusion barrel and lead screw systems stand as indispensable elements within numerous industrial processes, especially those involving the extrusion of materials like plastics. The extrusion barrel, a cylindrical chamber, provides a dwelling for the material being processed, while the lead screw, a threaded rod, propels the material through the barrel. Together, these components harmonize to form a remarkably efficient and precise system capable of extruding a diverse range of materials.

The extrusion barrel is typically forged from robust materials such as steel, chosen for their capacity to withstand the elevated temperatures and pressures characteristic of the extrusion process. It is meticulously designed to be externally heated using specialized heating elements, ensuring the material inside is adequately melted and primed for extrusion. To maintain the optimal material temperature during its journey through the barrel, cooling systems are often incorporated.

Operating as a precision component, the lead screw facilitates controlled material movement within the extrusion barrel. Powered by a motor, it revolves the screw, propelling the material forward at a carefully regulated pace. Crafted from durable, high-strength materials like steel, the lead screw undergoes meticulous machining to guarantee smooth and precise motion.

The extrusion barrel and lead screw system offer a distinct advantage in their ability to process a wide variety of materials. Plastics, rubber, and numerous other materials can be effectively extruded using this system, resulting in a diverse array of products, ranging from simple tubes to intricate profiles and shapes.

Another notable advantage of the extrusion barrel and lead screw system lies in its capacity to yield high-quality products with tight tolerances. The lead screw's precise control ensures consistent and accurate extrusion rates, while the heating and cooling systems maintain the material at the optimal temperature and viscosity levels, guaranteeing superior quality output.

Apart from its precision and versatility, the extrusion barrel and lead screw system excel in efficiency. This system can process substantial volumes of material swiftly and with minimal waste, making it an ideal choice for various industrial applications.

To ensure the seamless and efficient operation of the extrusion barrel and lead screw system, proper maintenance and lubrication are paramount. Regular maintenance routines help prevent wear and damage to the system's components, while appropriate lubrication ensures smooth operation with minimal friction.

One potential challenge that may arise with the extrusion barrel and lead screw system is wear and damage to the lead screw over time. Continuous movement can result in wear or damage, leading to reduced precision and efficiency. Regular inspection and replacement of worn components are vital to maintaining optimal system performance.

Overheating presents another potential issue for the extrusion barrel and lead screw system. Insufficient cooling or processing materials that are too hot can cause overheating, resulting in component damage and decreased efficiency. Proper cooling and temperature control measures are indispensable for preventing such occurrences.

The extrusion barrel and lead screw system epitomize a highly versatile and efficient solution employed across a wide range of industrial applications. With diligent maintenance and lubrication, this system can provide many years of reliable and precise operation, cementing its status as a vital component in various manufacturing processes.

Overall, the extrusion barrel and lead screw system play a pivotal role in numerous industrial processes, and their precision, efficiency, and versatility make them indispensable tools in manufacturing applications. By implementing thorough maintenance and lubrication practices, manufacturers ensure the seamless and efficient operation of this system, enabling them to produce high-quality products rapidly and with minimal waste.

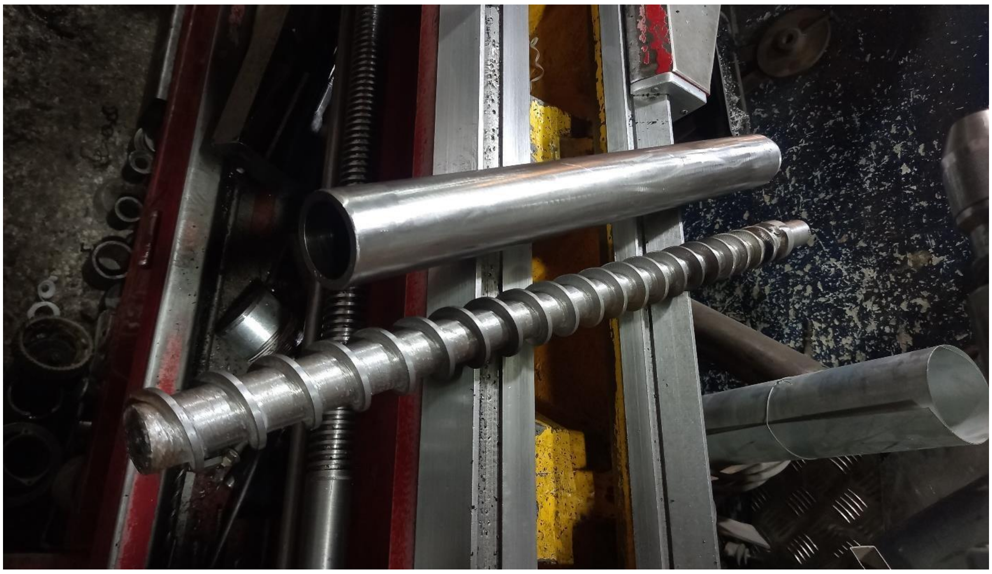


Figure 46: Extrusion Barrel and Lead Screw

Chapter 12

Coupling

12.1 Description:

Couplings are a crucial component used to join a motor and a lead screw. The primary function of couplings is to connect two shafts or rotating components, allowing them to transmit torque and rotational motion. When it comes to motor and lead screw couplings, there are various types to choose from, including flexible, rigid, and servo couplings. In this article, we will discuss the different types of couplings used to join motor and lead screw.

Flexible couplings are a popular choice for joining motors and lead screws. They are ideal for applications that require high-speed rotation or torque transmission. Flexible couplings can compensate for misalignments between the motor and lead screw, reducing wear and tear on the components. They are also useful for applications that require vibration damping or shock absorption. Flexible couplings come in various materials, including elastomers, steel, and aluminum, making them suitable for different environments and applications.

Servo couplings are a specialized type of coupling used to join motor and lead screw in servo applications. Servo couplings are designed to transmit torque with high precision and accuracy. They are ideal for applications that require high precision and accuracy, such as robotics and automation. Servo couplings are also useful for applications that require high torque transmission and high speed rotation. Servo couplings come in various materials, including aluminum and steel, making them suitable for different environments and applications.

Miniature couplings are a specialized type of coupling used to join small motors and lead screws. Miniature couplings are designed to be lightweight and compact, making them ideal for applications with limited space. They are also useful for applications that require high torque transmission and high speed rotation. Miniature couplings come in various materials, including aluminium and plastic, making them suitable for different environments and applications.

Beam couplings are a type of coupling used to join motor and lead screw in applications that require high precision and accuracy. Beam couplings are designed to transmit torque with high precision and accuracy, making them ideal for applications that require high precision and accuracy, such as robotics and automation. Beam couplings are also useful for applications that require high speed rotation and high torque transmission. Beam couplings come in various materials, including stainless steel, making them suitable for different environments and applications.

Jaw couplings are a type of coupling used to join motor and lead screw in applications that require shock absorption and vibration damping. Jaw couplings are designed to absorb shock and dampen vibration, reducing wear and tear on the components. They are ideal for applications that require high speed rotation and high torque transmission. Jaw couplings come in various materials, including steel and aluminum, making them suitable for different environments and applications.

Bellows couplings are a specialized type of coupling used to join motor and lead screw in applications that require high precision and accuracy. Bellows couplings are designed to transmit torque with high precision and accuracy, making them ideal for applications that require high precision and accuracy, such as robotics and automation. Bellows couplings are also useful for applications that require high speed rotation and high torque transmission. Bellows couplings come in various materials, including stainless steel, making them suitable for different environments and applications. Oldham couplings are a type of coupling used to join motor and lead screw in applications that require high misalignment capacity.

Figure 47: Jaw Coupling for Joining Motor and Lead Screw

Chapter 13

Diameter Measuring Assembly

13.1 Description:

A diameter measuring assembly consists of a depth gauge and other components that play a crucial role in industrial processes involving filament extrusion. The depth gauge is a key part of this assembly as it accurately measures the diameter of filaments.

The depth gauge typically comprises a rod or blade with markings indicating the distance from the tip to the reference surface. To measure the filament diameter, the depth gauge is placed perpendicular to the filament's axis, and the blade is adjusted until it touches the filament. The measurement can then be read from the gauge, providing an accurate diameter reading.

The use of a depth gauge offers several advantages in measuring filament diameter. Firstly, it provides high accuracy, making it suitable for measuring small diameters typically associated with filaments. Additionally, it is easy to operate, making it practical for industrial settings where efficiency is essential.

Durability is another advantage of depth gauges. They are designed to withstand rough handling and are made from durable materials that resist wear and tear, ensuring long-lasting performance.

Moreover, depth gauges offer versatility, as they can measure the diameter of various filaments, including plastics, metals, and other materials commonly used in industrial processes.

The diameter measuring assembly is useful for ensuring the filament meets the required specifications, maintaining consistent quality in industrial settings. It also serves as a troubleshooting tool, quickly identifying any issues during the production process and allowing for prompt adjustments.

In addition to filament diameter, the assembly can measure other dimensions, such as sheet thickness, expanding its utility across a range of applications.

Real-time monitoring capabilities enable the diameter measuring assembly to detect and address problems promptly, improving production efficiency.

Overall, the diameter measuring assembly, with its depth gauge as a key component, plays a vital role in industrial processes, offering accuracy, durability, versatility, and efficiency in measuring filament diameter.

We built our diameter measuring assembly by using **3D printed base, digital tread depth gauge, 3 mm screws, 3 mm bearings and rubber bands**.

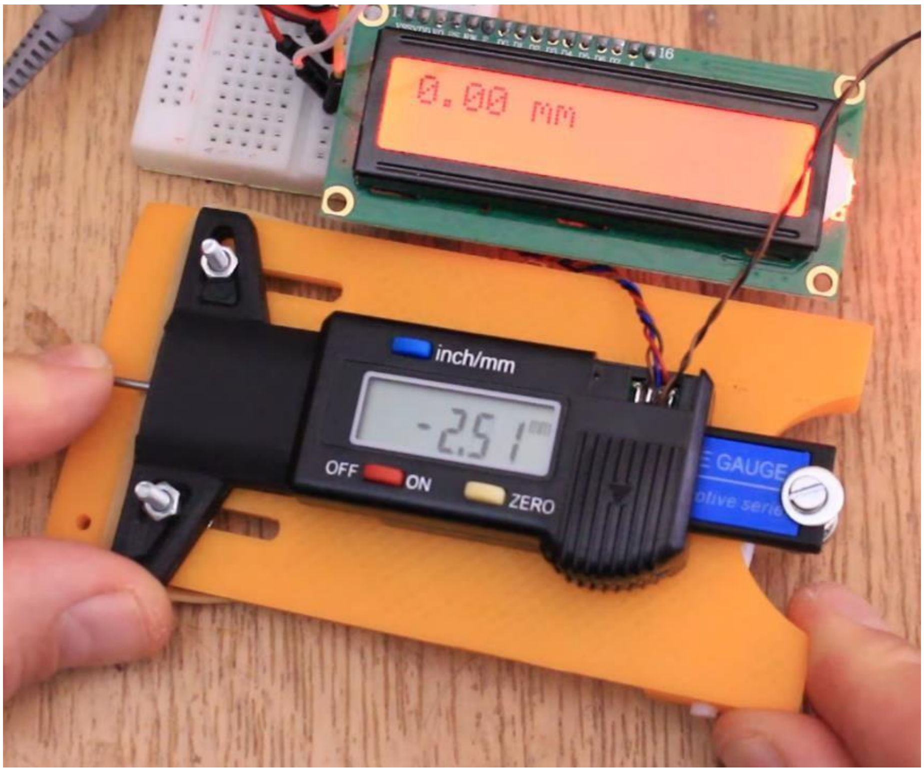


Figure 48: Filament Diameter Measuring Assembly

Chapter 14

Spool Holding Mechanism

14.1 Description:

The spool holding mechanism is an essential component of a filament extruder system that ensures proper management and controlled unwinding of the filament spool during the extrusion process. This mechanism plays a crucial role in maintaining a consistent filament tension, preventing filament tangling or knotting, and facilitating smooth filament feeding into the extruder.

There are various types of spool holding mechanisms used in filament extruder systems, each designed to suit different requirements and filament spool sizes. One common type is a spool holder with a central spindle. The spindle is typically mounted on bearings to allow smooth rotation of the spool. The filament spool is mounted on the spindle, and its rotation is regulated by a brake or tensioning system.

The brake or tensioning system provides adjustable resistance to the rotation of the spool. It helps control the unwinding speed and tension of the filament, ensuring consistent and controlled feeding into the extruder. The tension can be adjusted based on the specific filament characteristics and extrusion requirements.

Another type of spool holding mechanism utilizes a pneumatic or mechanical clamping system. This system securely holds the filament spool in place to prevent it from rotating freely during the extrusion process. The clamping mechanism can be easily adjusted to accommodate different spool sizes and ensure a stable and controlled filament supply.

In some advanced filament extruder systems, automated spool handling mechanisms are employed. These mechanisms incorporate sensors and feedback systems to monitor and regulate filament tension, spool rotation speed, and filament presence. They can automatically adjust the tension and control the spool rotation to optimize filament feeding and minimize the risk of filament jams or misfeeds.

Additionally, filament extruder systems may include features such as filament guide tubes or rollers. These components guide the filament from the spool to the extruder, reducing friction and minimizing the chances of filament tangling or twisting.

When designing a spool holding mechanism for a filament extruder system, considerations should be given to the weight and size of the filament spool, the desired filament tension, the smoothness of filament feeding, and ease of spool replacement. The mechanism should be robust, reliable, and easily adjustable to accommodate various spool sizes and types of filaments.

In conclusion, the spool holding mechanism is a critical part of a filament extruder system. It ensures proper management of the filament spool, controlled unwinding, and consistent filament feeding. Various types of mechanisms, including spindle-based holders, clamping systems, and automated handling mechanisms, can be employed to meet specific extrusion requirements. Designing an effective spool holding mechanism requires considering factors such as filament tension, spool size, and ease of use, ultimately contributing to the overall success and efficiency of the filament extrusion process.

Unfortunately, we could not fabricate a spool holding mechanism in our project due to shortage of funds. However, the fabrication of Spool holding mechanism is planned to be executed considering the budget in future.

Figure 49: Spool Holder Mechanism

RESULTS/IMPLEMENTATIONS:

The project yielded significant results and successful implementations in the field of filament production and recycling using a 3D printing filament extruder. Several key implementations were carried out, showcasing the capabilities and versatility of the extrusion process.

Firstly, the project successfully produced two samples of **Recycled PLA filament**. By employing a filament extruder, plastic waste materials were processed and transformed into usable filament. The extruder operated at temperatures of **175°C** and **180°C,** effectively melting the recycled PLA material and extruding it into filament form having diameter **1.4-2.1 mm.** This implementation demonstrated the viability of recycling PLA filament and showcased the potential for reducing environmental waste in the 3D printing industry.

Furthermore, the project also focused on producing **PLA filament from pellets,** a common form of raw material used in filament production. A sample of PLA filament was successfully produced using the extruder at a temperature of 180°C. This implementation highlighted the versatility of the filament extruder, which can handle different types of raw materials and effectively convert them into high-quality filament suitable for 3D printing applications. The optimum temperature range for PLA extrusion is found to be **170°C-180°C.**

The successful production of these filament samples signifies the effectiveness of the extrusion process in transforming raw materials into usable filament. The project demonstrated the precise control of temperature and extrusion parameters required for consistent filament production. The resulting filament samples exhibited desirable characteristics such as uniform diameter, good printability, and compatibility with 3D printers.

These implementations have important implications for the 3D printing industry. By showcasing the ability to produce recycled filament and effectively utilize raw materials such as PLA pellets, the project contributes to the promotion of sustainable practices and resource conservation. The use of recycled filament reduces reliance on new filament production and lowers the environmental impact associated with plastic waste.

In conclusion, the project successfully implemented the production of two samples of recycled PLA filament at temperatures of 175°C and 180°C, as well as one sample of PLA filament from pellets at a temperature of 180°C. These implementations highlight the versatility, efficiency, and sustainability of the filament extrusion process. The successful transformation of plastic waste and raw materials into high-quality filament opens up possibilities for reducing waste, exploring new materials, and fostering a more environmentally friendly 3D printing ecosystem.

Figure 50: Original PLA Filament

Figure 51: Recycled Filament at 175 Degree Celsius

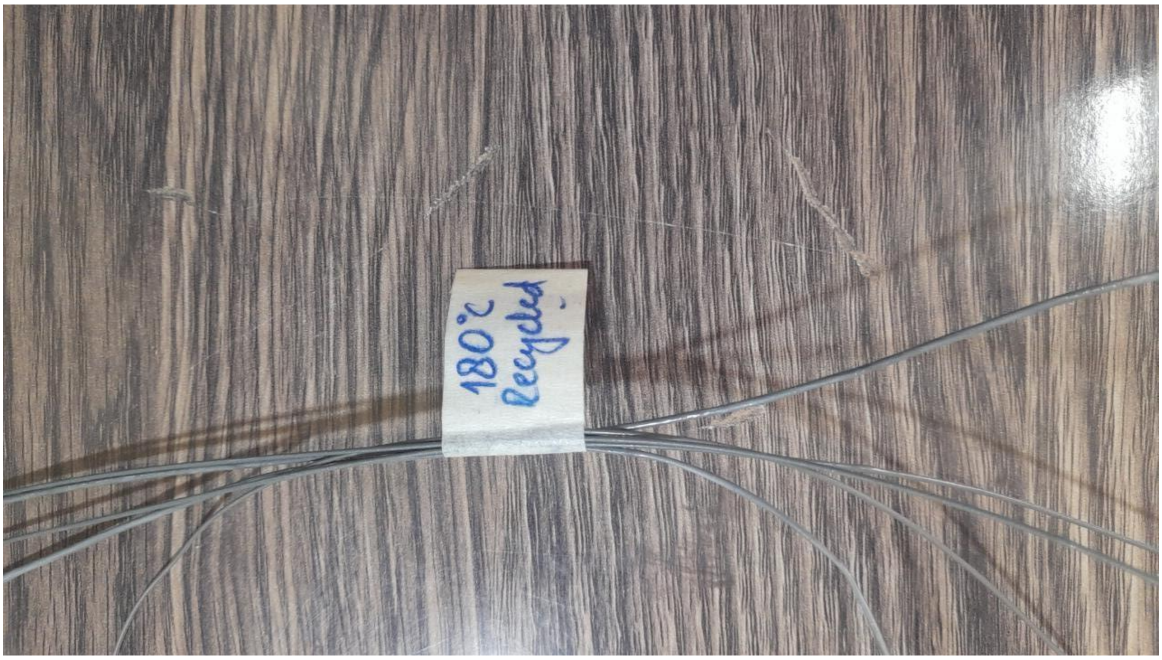


Figure 52: Recycled Filament at 180 Degree Celsius

Figure 53: Filament produced from pellets at 180 Degree Celsius

LIMITATIONS:

Material Compatibility:

3D printing filament extruders have limitations when it comes to processing certain materials. They may not be suitable for extruding materials with high melting points or those that require specific processing conditions such as PEEK, Polyether Sulfon.

Filament Strength and Properties:

The mechanical properties of recycled 3D printed filaments produced by filament extruders may not be as consistent or robust as those of commercially manufactured filaments. This can result in reduced strength, flexibility, and overall performance of printed objects. However, the strength can be increased by blending wasted material with some percentage of virgin material.

Time and Efficiency:

Producing filament using a filament extruder can be a time-consuming process. It involves shredding and processing the raw material, extrusion, cooling, and spooling. Compared to purchasing ready-made filaments, the production time can be a significant limitation.

Complexity:

Operating and maintaining the equipment, including calibration and troubleshooting, may require technical expertise and add to the complexity.

Filament Contamination:

During the filament recycling process, impurities and contaminants may be introduced into the extruder, affecting the quality of the filament produced. This can result in print defects or clogging of the printer nozzle.

Color Variation:

Achieving consistent color in 3D printing filament extrusion can be challenging, especially when using recycled materials. Variations in color may limit the aesthetic appeal and uniformity of printed objects.

Specialized Filament Types:

Filament extruders may struggle to produce specialized filaments with unique properties, such as conductive filaments or composite materials. These types of filaments often require complex manufacturing processes and precise material mixing ratios.

Safety Considerations:

Filament extruders involve heating and processing materials, which can pose safety risks if not handled properly. Operators should be cautious of potential hazards, such as high temperatures, fumes, and exposure to hazardous materials.

RECOMMENDATIONS FOR FUTURE WORK:

Introduction of Shredder:

Implement a shredder as part of the filament production/recycling system. This addition will enable the efficient breakdown of plastic waste materials into smaller, more manageable pieces, enhancing the recycling process and reducing material preparation time.

Enhanced Lead Screw Design:

Explore advanced lead screw designs that can improve filament extrusion precision and control. Consider incorporating features like using alloy steel with low friction coatings, nitriding, or dual-threaded screws for more efficient and accurate filament extrusion.

High Power Motor Integration:

Integrate a high-power motor to optimize the extrusion process. A more powerful motor can increase the extrusion speed and allow for the processing of a wider range of materials, including those with higher melting points.

Output Rate Improvement:

Focus on optimizing the output rate of the filament extruder. This can be achieved by refining the extrusion process parameters, enhancing the heating and cooling systems, and improving filament spooling mechanisms to increase overall productivity.

Filament Quality Monitoring:

Incorporate quality monitoring systems into the extruder setup. Utilize sensors or vision systems to detect and eliminate filament defects such as air bubbles, inconsistencies, or impurities, ensuring higher quality output.

Integration of Filament Cooling Mechanisms:

Improve the filament cooling system to enhance the filament's structural integrity and dimensional accuracy. Consider incorporating features such as forced air cooling or water cooling to efficiently solidify the extruded filament.

Safety Enclosure Implementation:

Install a safety enclosure around the filament extruder to minimize potential risks associated with heat, fumes, and moving parts. The enclosure should provide adequate ventilation, temperature control, and safety interlocks to ensure a secure working environment.

User-Friendly Interface:

Develop a user-friendly interface or control panel that simplifies the operation of the filament extruder. Integrate features like touchscreen controls, pre-configured material profiles, and intuitive settings adjustment to enhance the overall user experience.

Material Compatibility Expansion:

Expand the range of materials compatible with the filament extruder. Investigate new materials, such as bio-based or flexible filaments, and optimize the extrusion process parameters accordingly to accommodate a wider variety of filament options.

CONCLUSIONS:

In conclusion, the project focused on the development and utilization of a 3D printing filament extruder for filament production and recycling. Through the course of the project, significant progress has been made, highlighting both successes and areas for improvement. The successful demonstration of producing and recycling 3D printing filament using a filament extruder underscores the potential for reducing material waste and promoting sustainability within the industry. However, the project also revealed limitations such as material compatibility issues, variations in filament quality, and challenges in maintaining consistent filament diameter. Recommendations for future work were provided, including enhancements to lead screw design, integration of high-power motors, implementation of a shredder, introduction of safety enclosures, and focus on improving output rates and filament quality. Emphasizing user experience, material expansion, and safety considerations are crucial for the advancement of filament extrusion technology. Overall, the project's findings and recommendations serve as a valuable foundation for further research and development, paving the way for a more sustainable and efficient 3D printing ecosystem.

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APPENDIX-EQUATIONS USED

Equation 1:

Power required to melt the PLA is given by equation:

$$\boldsymbol{Power = mC_p\Delta T + m\Delta H_{fusion}}$$

Equation 2:

Net Volumtric flow rate that is extruded is given by:

$$\boldsymbol{Q_{EX} = Q_d + Q_p}$$

$$\boldsymbol{Q_{EX} = \frac{1}{2}\pi^2 D^2 HNcos\phi sin\phi - \frac{\pi Dsin^2\phi H^3 P}{12\eta Lm}}$$

Equation 3:

Shear Rate through the nozzle is given by:

$$\boldsymbol{\gamma(Round\ Channel) = \frac{4 \times Q}{\pi \times R^3}}$$

Equation 4:

Voulmetric Flow rate through nozzle:

$$\boldsymbol{Q_{Die} = \frac{\pi R^4 \Delta P}{8\eta L}}$$

Equation 5:

Condition for optimum operating point of extruder and to find maximum pressure:

$$\boldsymbol{Q_{Die} = Q_{EX}}$$

Equation 6:

Volumetric Solids Conveying Rate is given by Darnell and Mol Equation:

$$\boldsymbol{\frac{Q}{H} = \frac{\pi^2 Dh(D - h)tan\theta tan\phi}{tan\theta + tan\phi}}$$

Equation 7:

Mass Flow Rate is given by:

$$\boldsymbol{G = Q \times N \times Density\ of\ solid\ bed}$$

Equation 8:

Torque required is given by:

$$\boldsymbol{\tau = \frac{6.\mu.D.L}{H^2 tan\phi}(\frac{\pi^2.D^2.H.N.sin2\phi}{4} - \frac{\pi d_{N.V_N}^2}{4})}$$