UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DEVELOP A NEW MODEL OF LOW FRICTION OF HYBRID BEARING WITH PRECISSION GEOMETRY FOR LIGHT WEIGHT INDUSTRIAL APPLICATION

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BACHELOR OF MECHANIAL ENGINEERING TECHNOLOGY (AUTOMOTIVE) WITH HONOURS

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Faculty of Mechanical Technology and Engineering

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Muhammad Iman Haqiemi Bin Mohamad Zaki

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MUHAMMAD IMAN HAQIEMI BIN MOHAMAD ZAKI

A thesis submitted

in fulfillment of the requirements for the degree of

Bachelor of Mechanical Engineering Technology (Automotive) with Honours

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2025

DECLARATION

I declare that this Choose an item. entitled "Develop a New Model of Low Friction of Hybrid Bearing with Pricission Geometry for Light-Weight Industrial Application" is the result of my own research except as cited in the references. The Choose an item. has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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TAJUK: **DEVELOP A NEW MODEL OF LOW FRICTION OF HYBRID BEARING WITH PRECISSION GEOMETRY FOR LIGHT WEIGHT INDUSTRIAL APPLICATION**

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DEDICATION

I dedicate this work to my dear parents and Dr. Muhammad Ilman Hakimi Chua Bin Abdullah who has always believed in me and offered their support. Your encouragement and guidance have inspired my motivation and I would like to draw strength from them in order to face the difficulties. I am so thankful for your constant companionship in my life and for being such a great friend. This work is a reflection of the immense change you have made in my journey and to that, I give this to you with a grateful and thankful heart.

ABSTRACT

Bearing systems play a crucial role in a wide range of engineering applications, enabling and supporting motion while ensuring the efficient transfer of forces. Among these, thrust ball and roller bearings are widely recognized for their ability to accommodate axial loads during rotation. However, conventional designs of these bearings often suffer from inefficiencies due to frictional forces, resulting in increased energy consumption and wear over time. Addressing this challenge requires innovative approaches that not only reduce friction but also improve the overall structural stiffness and performance of the bearings. This study proposes the development of a novel self-organizing hybrid bearing structure designed specifically for lightweight applications. The focus is on optimizing the geometry of the bearing to minimize friction and enhance mechanical stability. Using Computer-Aided Design (CAD) software, specifically CATIA V5, advanced bearing designs were created with special attention to critical parameters such as contact angle, groove geometry, and ball diameter. These design modifications aim to significantly reduce energy dissipation and improve the operational efficiency of the bearings. The bearing prototypes were fabricated using Selective Laser Sintering (SLS), a rapid prototyping method that enables precise construction of complex designs. The performance of the proposed designs was evaluated through detailed simulations in SIMSOLID, which analyzed key factors such as contact forces, load distribution, and structural stability. The Rectangle geometry stood out as the best performer, offering balanced load distribution and reliable structural stability. While the Square and Circle designs excelled in specific areas, their overall performance was less consistent. The Solid and Triangle geometries were less efficient due to higher forces and moments. Fabrication challenges, such as uneven sintering and porosity from recycled PA12 powder, required design adjustments to address material and 3D printing limitations. Despite these hurdles, the optimized designs significantly reduced energy loss and improved stability, making them ideal for lightweight, energy-efficient applications. This study highlights how geometry optimization and advanced fabrication techniques can enhance bearing performance while promoting sustainability with recycled materials.

ABSTRAK

Kajian ini menumpukan kepada penambahbaikan bebola galas tujahan dengan meneroka teknik reka bentuk canggih dan kaedah pembuatan moden. Dengan menggunakan serbuk PA12 dan teknologi *Selective Laser Sinter*ing (SLS), prototaip bebola galas hibrid yang inovatif telah dihasilkan dan dikaji. Reka bentuknya, dimodelkan dalam CATIA V5 dan dianalisis menggunakan SIMSOLID, menyelidiki bagaimana pelbagai konfigurasi geometri bulat, segi tiga, segi empat sama, dan segi empat tepat mempengaruhi prestasi dari segi integriti struktur, pengurangan geseran, dan pengagihan beban. Proses pembuatan menghadapi cabaran seperti keliangan, penyinteran yang tidak sekata, dan lekatan lapisan yang lemah. Masalah ini berpunca daripada sifat bahan kitar semula dan ketidakefisienan mesin seperti turun naik suhu dan penyelarasan laser yang tidak tepat. Walaupun menghadapi halangan ini, ujian menunjukkan peningkatan prestasi yang ketara. Reka bentuk segi empat sama menunjukkan prestasi terbaik, membuktikan bagaimana pengurangan kawasan sentuhan permukaan boleh meningkatkan kecekapan dan kestabilan. Prototaip galas telah dihasilkan menggunakan *Selective Laser Sintering* (SLS), kaedah prototaip pantas yang membolehkan pembinaan reka bentuk kompleks dengan tepat. Prestasi reka bentuk yang dicadangkan dinilai melalui simulasi terperinci menggunakan perisian SIMSOLID, yang menganalisis faktor utama seperti daya sentuhan, taburan beban, dan kestabilan struktur. Geometri Segi Empat didapati sebagai prestasi terbaik, menawarkan pengagihan beban yang seimbang dan kestabilan struktur yang boleh dipercayai. Walaupun reka bentuk Segi Empat Sama dan Bulatan cemerlang dalam bidang tertentu, prestasi keseluruhannya kurang konsisten. Geometri Pepejal dan Segitiga didapati kurang efisien disebabkan oleh daya dan momen yang lebih tinggi. Cabaran fabrikasi, seperti sintering yang tidak sekata dan keliangan daripada serbuk PA12 kitar semula, memerlukan penyesuaian reka bentuk untuk menangani had bahan dan percetakan 3D. Walaupun menghadapi cabaran, reka bentuk yang dioptimumkan berjaya mengurangkan kehilangan tenaga dan meningkatkan kestabilan dengan ketara, menjadikannya sesuai untuk aplikasi ringan dan cekap tenaga. Kajian ini menekankan bagaimana pengoptimuman geometri dan teknik fabrikasi maju dapat meningkatkan prestasi galas sambil mempromosikan kelestarian melalui penggunaan bahan kitar semula.

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CHAPTER 1

INTRODUCTION

1.1 Background

Ball thrust bearings, also known as axial ball bearings, have been actively used in applications since the mid-1800s. They are designed to facilitate axial motion by reducing friction between two interacting parts. Sven Winquist, a Swedish designer, introduced a novel kind of ball thrust bearing in 1907. This design used two sets of races: one for the balls to operate on and another to support the assembly. Winquist developed the development of a highly effective system for applying the double-row, self-aligning ball bearing in automotive and several industrial applications.

Development of the ball thrust bearing was further discovered during the Second World War when the massive demand for high-quality bearings was put onto the market for military avionics gear and aircraft (Shigley, 2004). It became a development when the maximum demand for accurate and rigid ball thrust bearings was required. Today, ball thrust bearings are important to the propulsion system and its application in vehicles and aircraft, aerospace, and general industrial equipment. These bearings find application in a vast field of applications since they have now been developed for both radial and axial stresses. The enhancement of the geometry of the ball thrust bearing is currently being concentrated on to upgrade its performance in new fields of application.

This research is going to focus on the influence of various geometries of holes circular, triangular, square, and rectangular on the outer ring, which is going to reduce the area of action between the ball bearings and the applied contact pressure on the rolling elements depending on the length of the contact surface. It is therefore hypothesized that the proper geometrical construction of an optimized geometry would result in considerable improvements in the stability properties of the bearings. Most of the traditional bearing designs, however, often follow a fixed logarithmic spiral curve, and a lack of literature can be observed to address how to provide proper modifications of the groove geometry to achieve essential enhancements in the bearing characteristics (Hashimoto, 2008).

1.2 Problem Statement

Low-friction hybrid bearings with leading-edge geometries are highly critical in the modern industrial lightweight sector, where precision motion control is essential. Existing bearing solutions often fail to deliver optimal performance due to limitations in friction reduction, load capacity, and durability. Bearings play a silent yet vital role in reducing friction in machinery and industrial systems, enabling smooth operation and efficiency.

As technological advances drive increasing demands for efficiency, the need for bearings that are more frictionless, lighter, and better suited for modern manufacturing processes has grown paramount. High friction in bearings leads to energy loss and accelerated wear, affecting machinery lifespan and overall efficiency.

This project focuses on reducing the coefficient of friction in bearing development to improve performance, increase operational lifespan, and reduce maintenance costs. Traditional bearing designs are often too heavy, limiting their application in lightweight machinery and systems where weight savings are crucial.

To address these limitations, this project explores innovative manufacturing techniques such as 3D printing, specifically Selective Laser Sintering **(SLS)**. By employing SLS, complex and lightweight bearing geometries can be achieved, enabling mass reduction and improved design flexibility. Lightweight bearings ensure higher efficiency, easier handling, and simpler installation, contributing to operational excellence.

Traditional manufacturing methods often fail to deliver the intricate geometries and lightweight features required in modern industrial applications. This project adopts additive manufacturing techniques, primarily SLS, to introduce novel designs and configurations previously unattainable. These advancements minimize material wastage while enhancing bearing performance and longevity, making them applicable across various industries.

This research aims to transform bearing technology into solutions that are more effective, durable, and sustainable, driving industries toward a future of innovation and increased productivity.

1.3 Objective

The project objectives are as follows:

1. To designed a new hybrid bearing feature with optimized geometrical.
2. To analyze the structural and performance aspects of the hybrid bearing using SIMSOLID.
3. To fabricate a new hybrid bearing feature with optimized geometrical.

1.4 Scope of Research

The scope of this research is as follows:

1. Designing an optimized hybrid bearing geometry using CAD or CAE software, CATIA.

2. Conducting structural and tribological performance simulations of the hybrid bearing using SIMSOLID to evaluate factors such as stress distribution, load capacity, and deformation under operational conditions.

3. Fabricate the developed optimized hybrid bearing geometry using SLS machine.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

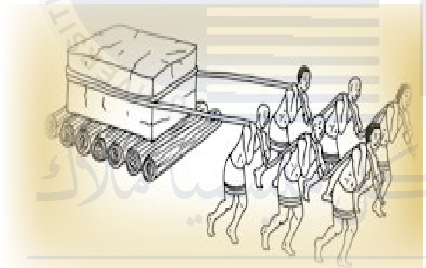
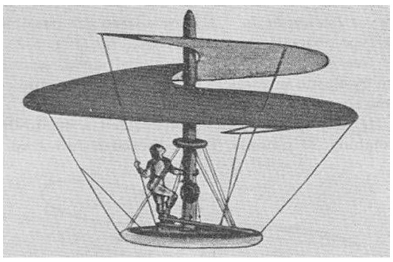
Bearing technology is one of the most cardinal technologies among the most mechanical systems applied today in industrial machines, vehicle transport, and many other instruments. After all, it is the bearings of the mechanism that ensure the difference between the moving parts, but without friction, due to which the movement smoothly and efficiently takes place. In the modern days, design and manufacture have considerably improved in the bearing careers, stimulated by the incessant demand for enhanced reliability, dependability, and energy efficiency across industries.

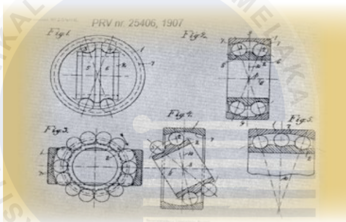
Conventional bearings use rolling or sliding elements that can take the loads and offer meager wear resistance. Those are the points where conventional methodologies are majorly limited to frictional losses, wear, and maintainability, especially under harsh conditions and in the quest for alternative approaches to bearing design, scientists and engineers made trials that led to the formulation of hybrid bearings as a novel approach. Most tools would not work nearly as well if they did not contain bearings. Although these can feel like mechanical components that do not have any design with them, the importance of them cannot be overstated. It is widely considered almost the backbone of the machinery industry, and one of its primary purposes involves enabling the lowest possible frictional rotation.

2.1.1 Overview History of Bearings

Bearings are the one thing that has stood the test of time. They have been there since the Stone Age. They are also crucial in several applications even to date. It is obvious to suitable bearings make it possible for to deliver to customers what they want. With our global purchasing network, sure that wherever in the world, get genuine bearing and PT products, making any possibility of receiving substandard products null and void.

Table 2.1 illustrates the evolution in bearing throughout various time periods, as source (Dean Payne).

Year	Descriptions
2600 BC 	In Ancient Egypt, roller bearings were used to move the enormous stone blocks in Pyramids.
40 BC 	The oldest example of a wooden ball bearing dates to the remains of a sunken Roman ship placed under Lake Nemi in Italy and belonged to a turntable.
1500 AD 	It is said that by the time da Vinci made his drawing designs of a helicopter, he used ball bearings, marking their first historical use in aircraft engineering.

17th Century	Galileo developed the first bearing with sealed elements.
1740 	John Harrison was the first to patent the caged-roller bearing for his H3 marine timekeeper. He did not know that he was using a modern form of a regulator clock design with the same type of bearing.
1794 	The first documented patent of the ball race was for Philip Vaughn, a citizen of Carmarthen in Wales, the concept for which states a spherical object tracking down a surface, such a surface is placed in the housing that houses it TR, which feeds the components.
1869 	The first patent was issued to the radial ball bearings, and it was to the Parisian bicycle mechanic Jules Suriray. The bearing was laid out on the first bicycle that would win in the first bicycle race in the whole world, given in Paris.

1898 	Received first patent on Timken tapered roller bearings. Henry Timken started his company the following year.
1907 	Sven Wingquist developed a new self-aligning version of the ball bearing, which facilitated massive progress in the field of the ball bearing and defined entirely new standards for the sector, thereby creating new impetus for further developments. Those were followed by the wire race bearing in 1934 and the vee groove bearing in 1968.
1917	American Bearing Manufacturers Association (ABMA) was established in 1917 as a result of a loosely structured fellowship of American bearing manufacturers at the time of World War I for the support in the production and manufacture of bearings.
The 1980s	Robert Schroeder invented the first bi-material plain bearing.

	
The 2000s  	Nowadays, ball and roller bearings have found enormous use in just about every type of industrial application, ranging from of wheel bearings in the automotive to ultra-high-speed bearings for dentistry drills, and so many others.

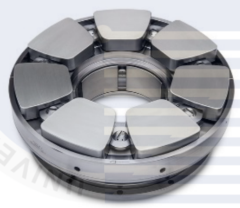
2.2 General Type of Bearing

Bearings are said to be one of the critical, integral, designed machine elements, which are meant to support loads and present the least possible amount of friction. There are many different kinds, each put to use for specific applications and conditions of operation. They are manufactured for our particular requirements, where we can control the range of movement a component can make. They are essential pieces, hence finding usefulness in various works in industries that help reduce motion with balance.

Table 2.2 Types of Bearing, source (NSK.com, n.d.)

Type	Description
Ball Bearing	Deep Groove Ball Bearings can take radial and axial loads and have different types for high-speed service. Angular Contact Ball Bearings are recommended to be used for the simple reason of carrying combined loads in high-speed service;

	that is, both radial and axial. Even in such an application where misalignment is expected, Self-Aligning Ball Bearings can be used due to their inherent characteristic of self-alignment.
Roller Bearing 	Cylindrical roller bearings can take up substantial radial load and are operated at medium speeds. Tapered roller bearings can withstand considerable loading in both radials and thrusts and are therefore used over a large range in automotive and commercial applications. Spherical Roller Bearings are intended to take high radial loads and moderate axial loads, and, therefore, they also have to cater for misalignment.
Thrust Bearing 	Ball Thrust Bearings are designed to operate efficiently at reduced speeds and under axial loads. Roller Thrust Bearings are to be operated under very high loads in which axial loads predominate. Radial Needle Bearings have been designed to offer a small radial dimension and high load capacity.
Needle Bearing 	Radial Needle Bearings consist of small cylindrical rollers and are suitable for situations where there is limited radial area but a need for high load capacity. On the other hand, Thrust

	Needle Bearings are designed to handle axial loads in compact designs.
Plain Bearing (Sleeve Bearings) 	Journal bearings are simple and generalized bearings, mainly used in large loads and low-speed applications. In contrast, linear bearings are manufactured especially for applying linear motion and are primarily used in automation and CNC machines and tools.
Fluid Bearing 	The fluid film in Hydrodynamic Bearings carries the load; this is hence a physiological difference in its shape that a slight variance is allowed. In Hydrostatic Bearings, the loaded area carries the load through an externally pressurized fluid, allowing it to develop perfect control.
Magnetic Bearing 	Passive Magnetic Bearings: are permanent magnet bearings that support loads without active control; thus, by definition, they are appropriate for application only with low-level loads. On the other hand, active magnetic bearings keep the shaft position through electromagnets and a control system, and frictionless and wear-free operation is experienced.
Composite Bearing	Ceramic bearings, instead, are made of ceramics in general: they have high-speed capacities and, in addition, they are resistant to corrosion and high

	temperatures. Metal polymer bearings are strong metals combined with low-friction polymers for the best performance in maintenance-free applications.

2.2.1 Hybrid bearing

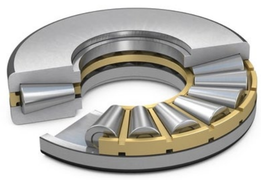
Finally considering this hybrid bearing based on the diversity that can be engineered into the bearings. We, therefore planned to incorporate the ball and roller bearings into the rolling element system of our prototype model in a move pointed to performance and other functional enhancements. This change in bearing type will have efficiency as a resultant effect and will allow one to experience smooth operations in the rotating process.

2.2.1.1 Roller bearing

Roller bearings are designed to bear heavy loads and control forces transmitted in both radial and axial directions. The significant types of roller bearings are:

Table 2.3 Overview of Different Types of Roller Bearings, source (NSK.com, n.d.)

Type	Description
Cylindrical Roller Bearing 	Single-row cylindrical roller bearings are used with high radial load at low speed. In double-row cylindrical roller bearings, the radial load capability increases with better stiffness. The multirow cylindrical roller bearings are applied under hard conditions, such as running over the rolling mills.
Tapered Roller Bearing	Single Row Tapered Roller Bearings shall be designed in such a manner that they shall take care of both radial and

	axial loads with excellent load-carrying capabilities. The Double Row Tapered Roller Bearing shall be used for increased load capacity and stiffness, particularly suitable for gearboxes and heavy machinery. The four-row tapered Roller Bearing is used for cases that relate to very high radial and axial loads—in the case of rolling mills.
Spherical Roller Bearing 	Likely to be Spherical Roller Bearings designed to work with heavy radial loads and to be able to handle substantial axial loads while still being able to tolerate some misalignment. Sealed Spherical Roller Bearings retain lubricants and drive contaminants out, increasing practical bearing life in harsh environments. These bearings can support high axial load and moderate radial strains. This is most suitable for applications that include misalignment.
Tapered Roller Thrust Bearing 	These bearings are designed so that they can easily withstand a significant amount of force in one direction. Usually, they are applied in demanding industries, for example, construction and mining; hence the type of equipment used to do such work is heavy-duty.
Spherical Roller Thrust Bearing 	These bearings can support high axial load and moderate radial strains. This is most suitable for applications that include misalignment.

2.2.1.2 Ball bearing

Ball bearings come in over thirty different types, all designed for a particular use and load it must withstand.

Table 2.4 Overview of Different Types of Roller Bearings, source (NSK, n.d.)

Type	**Description**
Deep Groove Ball Bearing 	These are some of the most common types. The construction of ball bearings uses deep raceway grooves and is equal to combined radial and axial loads; the best applications are found in motors, gearboxes, home appliances, and industrial machinery.
Angular Contact Ball Bearing 	These bearings are purposely designed to take the work that works at a time in only one direction and have angular contact of the race with the ball. Therefore, application in which high speed is involved include pumps, machine tool spindles, and electric motors.
Self-Aligning Ball Bearing 	Therefore, application in which high speed is involved include pumps, machine tool spindles, and electric motors. These bearings have two rows of balls, and a common concave sphered raceway in the outer ring, meaning they can take minor imbalances and usually are put to use on shafts in textile and agricultural machines.
Miniature and Instrument Ball Bearing	Examples of applications for these miniature bearings are: dentistry and health care equipment, small electric

	motors, and office automation requiring very precisely manufactured elements.
Thin Section Ball Bearing 	These bearings are lightweight with minimal cross-section relative to their diameter; hence, their applicability to robots, airplanes, and medical equipment.

2.3 Bearing properties

The evolution of bearings has been inspired by the need to satisfy various industrial demands in different operating environments. Important factors such as resistance to corrosion and substances, cost-effectiveness, a lightweight design, and durability have been important considerations in this process of development. These features make sure bearings function well in various settings, providing outstanding results while fulfilling specific industry demands.

Table 2.5 Bearing Properties

Properties	**Description**
Stainless steel	Stainless steel provides great resistance to corrosion, along with better durability. They have the ability to withstand very high or low temperatures, need not much maintenance, and are simple to keep clean standard grades such as AISI 440C, 304, and 316 are commonly used in various industries including marine equipment, food processing, and medical devices. Due to their versatility and

	reliability, they are crucial in industries where performance and longevity are of the highest priority.
Carbon steel	Carbon steel are popular for their durability and cost effectiveness. They show high tensile durability and strength, making them suitable for demanding applications in several sectors. While they do provide an acceptable degree of resistance to corrosion and can tolerate moderate temperatures, it is important to perform regular maintenance in order to prevent damage in corrosive conditions. However, their low price and reliability make them widely chosen for use in automotive parts, agricultural machinery, conveyor systems, and construction equipment, where achieving a balance between performance and budget is crucial.
Chrome steel	Chrome steel have become known for their excellent hardness, durability, and ability to resist wear and deformation. Composed of steel alloyed with chromium, these materials have outstanding durability and fatigue resistance, making them highly suitable for high-load and high-speed applications. Although they possess excellent corrosion resistance, they may not achieve the same degree as stainless steel bearings. However, their capacity to be used in various ways makes them extremely important in industries such as automotive, aircraft, industrial machinery, and precision equipment, where reliability and performance are of the highest priority.
Ceramic	Ceramic show outstanding reliability in tough conditions, sustaining elevated temperatures and showing higher longevity in comparison to steel counterparts. Due to their lightweight composition and little

	maintenance needs, these products are in high demand in industries that value reliability and durability, such as automotive, aerospace, and medical equipment.
Polymer plastic	Polymer plastic offer unique benefits in different industries. Due to their low weight, ability to resist corrosion, and self-lubricating qualities, they are ideal for demanding conditions where standard metal bearings may fail. Due to their non-metallic nature, they lack conductivity and show remarkable resistance to chemicals and moisture. These material are widely used in industries such as food and beverage, pharmaceuticals, and electronics, with a focus on maintaining hygiene, resisting chemicals, and minimizing friction. Due to their versatility and capacity to reduce maintenance costs, polymer plastic bearings are becoming more popular in modern engineering applications.
Hybrid	Hybrid use the advantages of both ceramic and steel bearings. They provide the durability and heat resistance typical of ceramics, while maintaining the affordability and low maintenance related to steel. Hybrid bearings are widely used in the automotive, aerospace, and industrial fields. They enable improved performance and cost-effectiveness, especially for situations where reliability is of the highest priority.

2.3.1 Material Description: Polymer Plastics (Nylon PA12)

This is usually achieved by using polymer plastic, such as Nylon PA 12, in making the prototype. This plastic has been popularly applied because of the numerous additive applications it has in use due to the flexibility associated with it and its multipurpose properties. High flexibility, surface finish, heat deflection, tensile strength, operating temperature range, and good tensile strength make the nylon PA 12 quite good material for many uses. It is one of the mainly used materials in 3D printing through additive manufacturing because of its broad operating temperature range and cheap cost.

Table 2.6 Properties for Nylon 12 and Nylon 11

Properties	**Nylon 12**	**Nylon 11**
Flexibility	Good	Excellent
Surface finish	Good	Excellent
Heat Deflection	Excellent	Good
Tensile strenght	Good	Excellent
Operationg Temperature Range	Excellent	Good
Price	Excellent	Good
Melting Temperature (20°C/min)	176 °C	201 °C
Flexural Modulus (+23°C)	1500 MPa	-
Charpy Impact Strength (+23°C)	4.8 KJ/m²	7.8 KJ/m²
Charpy Impact Strength (+23°C)	53 KJ/m²	N
Tensile Modulus	1650 MPa	1600 MPa

Tensile Strength	48 MPa	48 MPa
Elongation	18 %	45 %
Shore Hardness	75	75

2.4 Manufacturing of Bearing

There are many methods practiced in the industry related to the bearing manufacturing depending upon the type of bearing to be manufactured. All these methods help check the effectiveness of the bearings to meet different loads and situations with accuracy and dependable quality.

Table 2.7 Manufacturing of Bearing

Type of bearing	Manufacturing process	Description
Metal bearing	Material Selection	Select appropriate material to use when manufacturing bear- ing components made from steel alloys.
	Forging	Shape inner and outer rings to required forms.
	Machining	Special purpose machine rings to very high levels of accuracy in terms of size and finish.
	Heat Treatment	Expand the function of annealed rings by heating them in a way that enhances their surface hardness, mechanical strength, and resistance to abrasive wear.
	Grinding	It utilizes highly precise grinding

		methodologies in order to allow for a high amount of accuracy in terms of dimensional size and roughness of the surfaces.
Ceramic bearing	Material Selection Forming Sintering Grinding	For designing the bearing, choose intelligent ceramics like silicon nitride (Si3N4) or zirconia (ZrO2) for the bearing parts. Compact ceramics into molds in order to achieve the proper shape of bearings' parts like balls, rollers, and races. To give the ceramic particles the required density and strength, heat them in secure and selective conditions to high temperatures. Grind the sintered ceramic components in a fashion that leads to the required tolerance and surface finishes since the bearings must have tight running clearances and smooth surfaces.
Plastic bearing	Material Selection Injection Molding	Choose the correct technical polymers for its bears like Nylon PA 12 or PTFE based on given parameters like load support capability, wear and chemical suitability. It is one of the most common processes of manufacturing bearing components such as races, balls, or rollers through injection

		moulding processes, which involves injecting molten material into specifically designed moulds at high pressure and short duration.
	Cooling and Solidification	Carry out the process of cooling the moulded plastic components to avoid the formation of shrinkage or warps that may distort the shape or size of the components by ensuring that the geometrical tolerance is holds good.
	Finishing	Trim off any excess of material from moulded plastic parts, and put a fine finish on its surfaces to reduce any roughness and irregular contour.

2.4.1 Addictive Manufacturing

Additive manufacturing also known as 3D printing is an advanced manufacturing technique that involves detailing a product by successively adding substance layer after another layer with the aid of specific software as well as apparatus. This creative method adopts several processes in the development of artifacts and objects for use in additive manufacturing technology for include VAT Photopolymerization, Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion, Sheet Lamination, and Directed Energy Deposition.

Of all the processes outlined above, Powder Bed Fusion (PBF) is famed for its flexibility and accuracy. Thus, we considered the Selective Laser Sintering (SLS) process, Powder Bed Fusion technology, for our bearings' production. This technique involves the fixing of components with the help of a laser to form structures and objects of excellent strength and complexity by fusing powdered particles.

SLS and the other kinds of additive manufacturing introduced are presenting a new generation of manufacturing possibilities across a wide range of industries for tailored and efficient solutions that are complicated to produce in standard method.

Table 2.8 Type of Powder Bed Fusion

Type of Powder Bed Fusion	**Description**
Selective Laser Sintering (SLS)	Selective Laser Sintering (SLS) is an Additive Manufacturing technique that involves the use of a high power laser to fuse the Powder bed materials, mostly polymers or metal powders to produce a solid compacted three dimensional object. This process is well monitored to ensure the right level of accuracy by Computer control processes. One of the techniques used within the 3DP process is the laser that fuses successively layers of powder to the shape defined digitally. SLS technology is known for its versatility and effectiveness – utilizing both nylon and TPU to create highly intricate parts at high resolutions. It should also be noted that the application of this technology is possible not only in strictly technologically advanced sectors such as aerospace,

	automobile manufacturing, and healthcare. It can be applied to various kinds of products including prototype, tooling, and a part for final use in the manufacturing process.
Direct Metal Laser Sintering (DMLS)	SLS – Selective Laser Sintering, is a versatile process that uses powder coated parts applied to different kinds of powder and DMLS – Direct Metal Laser Sintering is a specific variety of SLS process, which is designed for metal coatings. DMLS retains a higher level of precision, acquires better surface finish, and mechanical characteristics, which are as good as those of the conventional manufacturing methods. It is thus utilized in developing working models, specialty and; limited production products in sectors such as aviation, automobiles, and health.
Electron Beam Melting (EBM)	Electron Beam Melting (EBM) is a type of additive manufacturing that employs an electron beam for the melting of metals in a preformed powder form. It is done in layers and this technique can be applied using titanium or cobalt-chromium alloys. The electron beam that is used originates from an electron gun and then it is accurately controlled to fuse the layer of metal powder in accordance with the design that is digital. This operation is carried out under a vacuum since it facilitates the production of metal parts that free from oxides and

	porosity with extremely desirable mechanical characteristics. This technology has other applications widely in the aerospace and medical industry and is used to fabricate delicate and intricate parts like aircraft brackets and orthopaedic implants.

2.5 Low Friction of Hybrid Bearing

They all refer to a force that resists or slows down, or has the potential to slow down, the relative motion of two objects that are in contact. Friction is that force experienced whenever two objects rub against each other or tends to do so with other. Static friction is that which occurs between solid materials while kinetistic frictions may occur between any two materials; either solid, fluid such as air, water or gases. However, when using the everyday context, friction refers to the force acting on the adjacent and touching surface that are both solid. This force is developed based on apparent defects that lock and cause the surfaces to interface and be delayed. This is because the surfaces in contact exert force of attraction to each other due to electromagnetic forces induced by the atoms and molecules of the two surfaces.

2,5.1 Review of Type of Friction

Friction is a force that acts against the movement or potential movement of two surfaces that are in touch with one other. It performs an essential purpose in our daily lives and in many mechanical systems. Many kinds of friction exist, each possessing unique attributes and practical uses.

Table 2.9 Type of Friction

Type of Friction	Description
Static Friction	Friction is the force by which one or both of the objects resist the free movement of another of the two objects, when the two bodies are in contact. To initiate the movement of a stationary object, it is essential to overcome the static friction force acting between the two objects. The static friction is mostly greater than the kinetic friction because the unsuitable surface texturing starts to interlock earlier.
Kinetic Friction	Friction is any resisting force formed between two interfaces that are, themselves, in correlated movement. It should be noted that kinetic friction is often less than the static, and depends not only on the characteristics of the contact surfaces and their velocities.
Rolling Friction	The force that acts to retard the movement of a body when it rotates on any phase of its periphery in contact with surface. Static and kinetic friction are already lower than rolling friction owing to the decrease in the contact area. It additionally holds the answer within the change of the surfaces and materials.
Fluid Friction	Fluid resistance on the other hand is the force that opposes the motion of an object through a fluid or in other words, it is defined as the force per unit area acting on an object submerged in a fluid. Drag, or the force that opposes the movement of an item through a fluid depends on the geometric properties of the object, velocity of the object, and r physical characteristics of the fluid such as

	viscosity and density.
Dry Friction	Dry friction is that type of friction which arises when two solids surfaces come to rest on each other they do not use any sort of liquid in between. The value of this friction depends upon the nature of the two surfaces in contact and their measurable characteristics. Static friction is the frictional force that opposes a body when it stands on a surface whereas dynamic friction is the frictional force that opposes the body while is in motion.
Lubricated Friction	This tribological situation is characterized by the creation of opposition to movement between two solid surfaces facilitated by a lubricating agent. Lubrication can be described as a process that minimizes friction and wear by applying a thin film that provides minimal contact between the two operating surfaces. Evaluating efficiency and durability is important when it comes to machinery.Machinery needs should involve efficiency and durability because it is important in any mechanical equipment.

2.5.1 Dry Friction

Dry friction on the other hand refers to the resistance force that is experienced between the boundary of two contacting surfaces and which is in a state of relative motion. This force called friction and acts in the direction opposite of the motion of body and is frequently used in several mechanical and engineering applications. There exist two primary categories of dry friction: Comparing the two forces present in the system, the forces are classified as static friction and kinetic friction.

Static friction that is sometimes referred to as stiction, acts to retard the initial motion of surfaces that are currently stuck. The static friction comes to play when the two surfaces are not in motion and it increases with an increase in the applied force in direct relation so as to reach its maximum. Once an object gets over the rub surface, both the surfaces start moving and the friction enters the kinetic phase.

The friction that arises when moving objects are relative to each other is known as kinetic friction or sliding friction or dynamic friction. Hence, the kinetics friction is always lower than the maximum possible static friction and is also more or less constant not like the static friction. It serves to slow two moving surfaces down and applies a constant force of friction to act against the movement.

Other factors that impact the frictional force include the materiel in contact which is represented by the coefficient of friction or friction material represented by the symbol μ while the normal force or force applied by one surface perpendicularly to the other is represented by N. The following formula can be used to express the frictional force:The following formula can be used to express the frictional force:

$$\boldsymbol{f = \mu N} \tag{2.1}$$

Table 2.10 Laws of Dry Friction

Law	**Description**
Coulomb's Law	This means that the amount of force that opposes and depends on the areas of contact between two surfaces is directly proportional with the force applied perpendicularly to those surfaces.
Amontons's Law	It is striking that the size of the real area of contact on the two

	surfaces does not influence the friction force.
Angle of Friction	The extent of the contact surface does not influences the frictional force, based on it's appearance. Angle of friction is in other words the angle at which the object is located on the surface of the body about to start moving.

2.5.2 Normal Force

Normal force is the additional force that the surface exerts in order to counter the force of attraction of the object placed on the surface with the ground. It is also perpendicular to the surface and forces a path through the cavity. When one places a book on a table, the table exercises a force upwards on the book this is in an attempt to counter balance the force of gravitation that would force the book to fall.

They are parts employed in the machinery to decrease the friction that happens in the rolling parts of an assembly. They quite frequently support very drive train components like rotating shafts and help these to work or rotate as required. The normal force has a great influence in the functionality of bearings When it comes to bearings, it is very important to identify the role of the normal force.

Similarly, if the object on the flat surface is at rest and has a mass of m, then the normal force can be ascertained using the second law of motion. Since the object is only exposed to forces acting vertically, the force that act on the object can be guessed to be the weight force which is acting on the object vertically. From W = mg equation, where W denote the weight and g denote the acceleration due to gravity, by using the normal force Fn, the following equation can be set up:

$$W + Fn = mg \tag{2.2}$$

2.5.3 Coefficient of Friction

This friction coefficient is symbolically represented by the Greek letter μ and it measures the ratio of the frictional force, F that is experienced between to surfaces to the normal force, L, which is exerted perpendicularly to the two aforementioned surfaces. This relationship is mathematically described by the formula:This relationship is mathematically described by the formula:

$$\mu = \frac{F}{L} \tag{2.3}$$

2.6 Geometry

Geometry the mathematical science deals mainly with the conformation and configuration of figures or mathematically, geometry is mainly concerned with the property and configuration of point, line surfaces and solids. It plays a vital role of an initial background of 'forms,' 'sizes,' and position in relation to one another of objects. Because of those general characteristics, geometry is employed in different areas and disciplines including art, engineering, architecture and physics and thus a significant branch of knowledge.

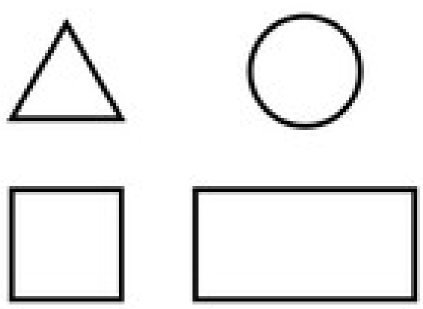


Figure 2.1 Common Geometry

2.6.1 Geometry Optimization in Design

Geometry optimization in design refers to the conceptualization of the most appropriate geometric form or layout of an object or a system required in the design process. This is important in enhancing the functionality and performance of the application that is to be used in the development of the system. Geometry optimisation has been a major research with new methodologies formulated and possibilities for further development being studied. From such studies, it is revealed that geometry optimisation fosters enhancement of design framework and application.

Table 2.11 Research on Geometry Optimization

Title	Description
Geometry Optimization in Structural Design	The engineer has come up with a new algorithm that has led to the practical application that poses a better Structural Performance and also reduces the amount of material used by approximately 15%. Future works will focus on fine-tuning the algorithm to handle complex structures and incorporate an eco-friendly material into the built environment.
Enhancing Performance of Mechanical Systems through Geometry Optimization	The optimization of rigid components utilize geometry exhibits an outstanding twenty percent increase in mechanical systems. Subsequent projects will take the results of this work further and apply it to a wider range of mechanical systems, as well as to have real-time adjustment functionalities.

Optimizing Aerodynamics in Automotive Design	Major relevance has been achieved with a 10% decrease in aerodynamic drag and improved reactivity of fuels. Future research activities should focus on electric vehicles and continue research efforts on drag reduction techniques.
Application of Geometry Optimization in Aerospace Engineering	A significant development has been marked as an impressive 12 % reduction in the weight of the components while at the same time the new Venturi has achieved a 5% improvement in efficiency. Further ongoing work will look into the application of further material technologies as well as an array of other methodology to accomplish further reductions in vehicle heaviness.
Boosting Application Performance through Geometry Optimization Frameworks	It is negligible that a framework has been set up in the provision of optimizing computational geometry for better application performance. Future upgrades are to cater for more complex use cases and to incorporate AI into the fabric of the technology, invisibly.
Geometry Optimization for Sustainable Architecture	Expressing a notable figure of 25% improvement in energy efficiency of buildings as geometric optimization is a good achievement. Further studies can be directed to improving the performance of integrating renewable energy systems with the architecture of buildings to ensure optimum functioning.

2.7 Simulation and Bearing Quality

In particular, we employed the SIMSOLID simulation platform for the evaluation of the proposed design and simulation of the corresponding problem. One can conveniently study the contact response and force distribution on various connections within the structure. By applying the right values in as input and performing the necessary simulations, we were able to glean a lot regarding the behaviour of the structure to different situations. Further, efficiency tests were conducted on bearing prototypes mounted in special testing machinery that incorporated acceleration and speed measuring equipment. It ensured the evaluation of bearing performance through recording of vibration frequencies at different speeds. In this way, through processing and analysis of the provided data, their effectiveness and expediency in real life situations in testing bearings were determined.

2.7.1 SIMSOLID

SIMSOLID is actually an advanced simulation tool that can assist in analyzing structures and even optimizing their designs. The significant feature of this system is the opportunity to study complex structures using relatively simple mathematical formalization and without going through the elaborate generation of meshes. It allows the performance of quick simulations of large assemblies and complex shapes and forms. Through the Material Property Database that is incorporated in SIMSOLID, engineers get to predict the structural integrity, weight, and performance of the designs under different load conditions. The structure also enables analysis of contact response and the forces on different connections which in turn enables analysis of real performance of the structure.

Figure 2.2 Structural Analysis for Rapid Design Iterations | Altair SimSolid

A primary advantage of SIMSOLID is its capability of handling large models, which is profitable when it comes to analyzing sophisticated assemblies that can be met in sectors such as car-making, aviation, and manufacturing industries. Further, the graphical user interface of the software is quite friendly and simple while using the auto-generated processes of the simulation, it becomes efficient. This leads to an ideal situation for engineers to be able to invest more time in fine-tuning the design of the model rather than having to spend a lot of time modelling the object.

In summary, SIMSOLID is a potent technology that engineers can apply in the simulation and design military to advance their flows in addition to affirming the functionality of their designs.

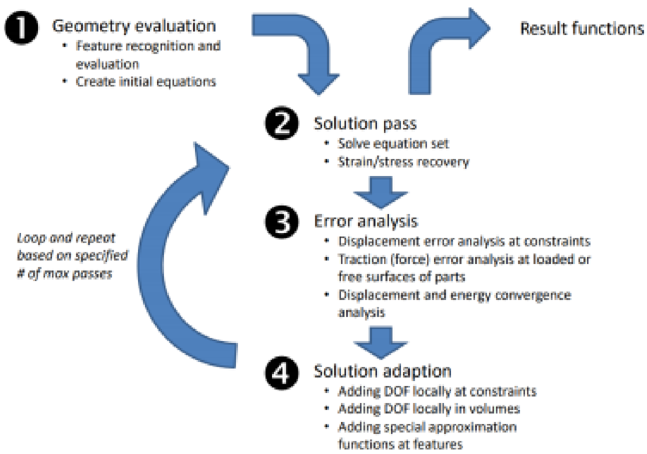


Figure 2.3 SIMSOLID Simulation Process, source (SIMSOLID Fast Start Training, 2019)

CHAPTER 3

METHODOLOGY

3.1 Introduction

In general, accuracy and effectiveness I considered two conflicting requirements in any evaluation model for low-friction hybrid bearings for lightweight applications. Accuracy referred to how closely the estimation results matched the "true" values of the hybrid bearings. Typically, the more accurate the model was, the higher resources it required (i.e., computational effort and time, amount of data, and cost). Meanwhile, effectiveness referred to the model's ability to estimate hybrid bearings with the least resources but with a reasonable loss of accuracy.

To provide a compromised solution to these conflicting requirements, an integrated approach based on EFM (Evolutionary Fuzzy Modeling) using RF (Random Forest) was presented in this project paper. The general concept behind the proposed model was to provide users with the ability to produce relatively accurate approximations of hybrid bearing values in lightweight applications. Relative accuracy was measured with respect to time series load flow simulations and hybrid bearing values provided by the local power utility company.

3.1.1 Flow Chart

Figure 3.1 illustrated some of the procedures used during this investigation. All the steps necessary to evaluate the effectiveness of new, improved geometry bearings were shown in the flow chart.

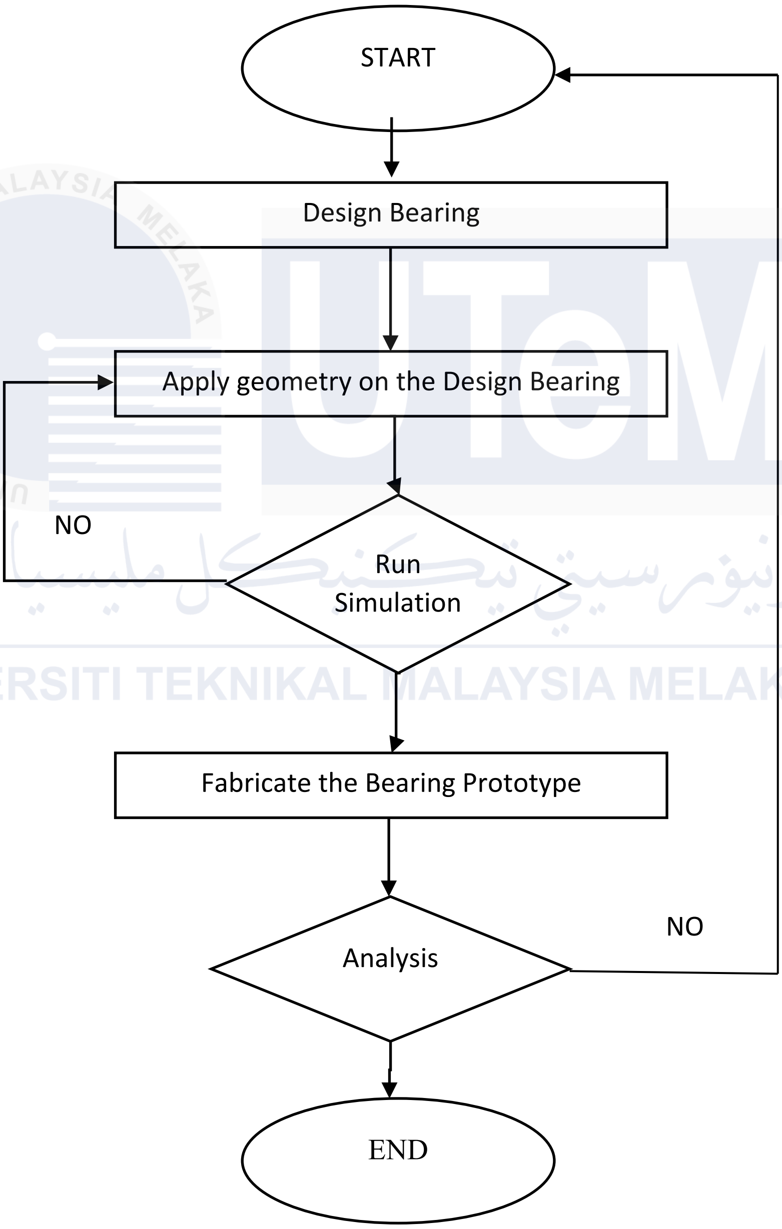


Figure 3.1 Flow Chart

3.2 Bearing Design

Acquiring a reference for a hybrid bearing suitable for lightweight applications involved a systematic process to ascertain the specific requirements of the intended use. Considerations such as load capacity, operational speed, temperature resilience, and environmental conditions were meticulously evaluated. Once the application requirements were known, it became easier to determine the best type of hybrid bearing to use. Various types of bearings were available in the industry, including ball bearings, roller bearings, needle bearings, and others.

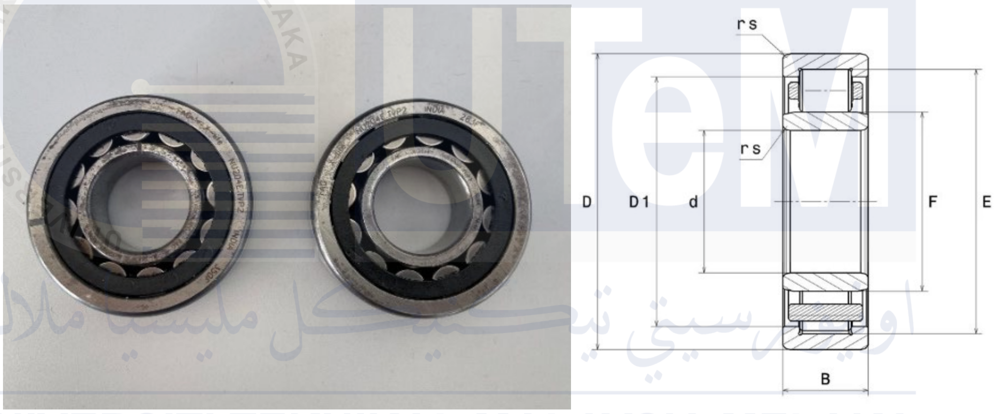
After deciding on the best type of bearing, it was necessary to acquire the specifications of the hybrid bearing from the manufacturer. These specifications encompassed crucial details such as load capacity, speed ratings, and other essential metrics. The geometric arrangement of the bearing part or assembly was then set to assist with the creation of a CAD model. Tools such as vernier calipers were used to gather measurements from the reference hybrid bearing.

Subsequently, constraints were applied to ensure that the part or assembly aligned with the specified design criteria. These constraints included dimensions, angles, and other geometric relationships. Additional features such as fillets, chamfers, and holes were incorporated into the model. Testing and refinement procedures were employed to verify compliance with the design criteria, utilizing simulation tools like SIMSOLID. Production drawings were created once the CAD model was finished, including detailed information on the hybrid bearing such as measurements, tolerances, and other important details.

Production drawings are created once the CAD model is finished and include detailed information on the hybrid bearing, such as measurements, tolerances, and other important details.

3.2.1 Reference Bearing Selection

The next step involved selecting tools and equipment required for the experiments, focusing on analyzing the bearing systems using SIMSOLID simulations. The roller bearing (Figure 3.3 A) supports the shaft during rotation. Structural data for the reference model was collected using visual observations, vernier calipers, and series codes on the bearings (Figure 3.3 B & Table 3.1). These measurements and observations provided the necessary input data for the simulation process, ensuring accurate evaluation of the bearing's structural performance and behavior.



A B

Figure 3.2 A. Cylinder Roller Bearing, B. Bearing 2D Structure Diagram with Labels

Table 3.1 Structure Data for Roller Bearing

Label	B	D	E	d	F	D1	rs
Dimension (mm) and Degree (º)	16	50.2	47	24	26.5	25.3	5º

3.2.2 Design in CATIA V5R21

As presented in Figure 3 and Figure 4, the hybrid bearing consisted of five components: the outer ring, inner ring, roller bearing, ball bearing, and bearing cage. We used CATIA V5R21 software to develop an optimized CAD model of the bearing based on the collected bearing data.

To create the bearing components, we started by selecting the component design feature in the program interface. We then utilized tools such as Sketch, Shaft, Pad, Pocket, Chamfer, Edge Fillet, Trim, and Circular Pattern.

Initially, I used the Sketch function to generate 2D shapes in various planes aligned with the X, Y, and Z axes. Next, we employed the Shaft and Pad functions to convert these shapes into three-dimensional objects that matched the intended design. Afterward, we applied the Pocket function to create voids within the 3D structures, such as those in the cage and the outer ring of the bearing.

Additionally, we used the Chamfer and Edge Fillet operations to smooth edges, thereby reducing friction and impact forces during rotation. Finally, we applied the Circular Pattern tool to replicate multiple instances of selected features, such as the square pattern on the outer ring, apertures in the bearing cage, and various shapes on the outer ring.

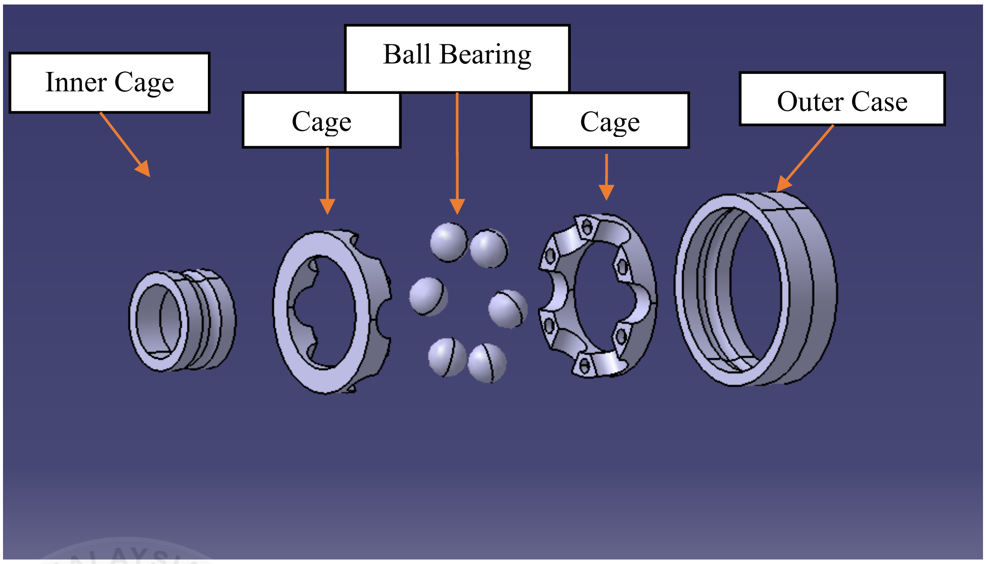


Figure 3.3 Bearing's Parts

3.3 Application Geometry on Bearing Design

The different holes created using the circular pattern and pocket functions were based on the dimensions listed in Table 3.2. Using the numbers and angles in Table 3.3, holes were created on the outer ring with the pocket function. Several holes surrounding the outer ring were generated using the circular design.

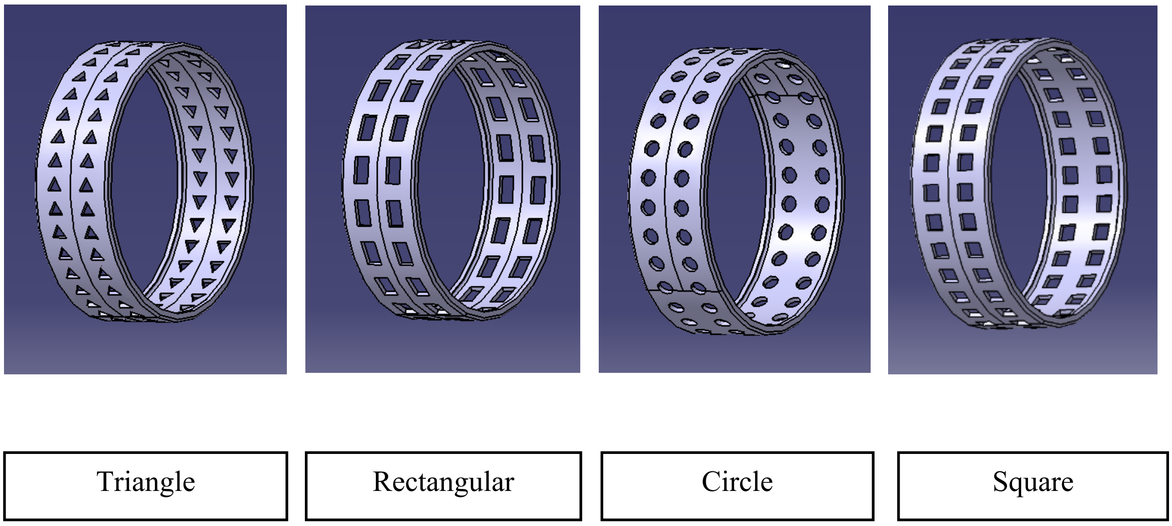


Figure 3.4 Different Geometry on The Outer Cage

Table 3.2 Dimension of Geometry Applied

Geometry	Square	Circle	Rectangular	Triangle
Dimension (mm)	3x3	4.2	5*3	3
Gap between geometry (mm)	2	2	2	2

Table 3.3 Total Number of Different Geometry and Angle Applied

Geometry	Square	Circle	Rectangular	Triangle
Total number	30	30	20	36
Angle (°)	12	12	18	10

3.4 Method of Simulation Process

Simulation was conducted using software to replicate the system and analyze its performance. It entailed specifying the geometry, imposing constraints, solving with numerical techniques, and analyzing the results. CAD models created in the previous chapter were transferred to SIMSOLID for simulation. Geometrical flaws in the CAD model design (Figure 3.6) were identified, and connections were manually built (Figure 3.7) to address any flaws.

Material properties were assigned to each component in the CAD models, and Non-Linear Structural Analysis was performed to predict performance. The outer ring was constrained, and the inner ring exhibited hinge and rotational inertia characteristics. Sliders were added to both the outer and inner rings for easy shifting. Finally, analyses to record reaction/contact forces and responses were performed, and data were collected for further reference and optimization.

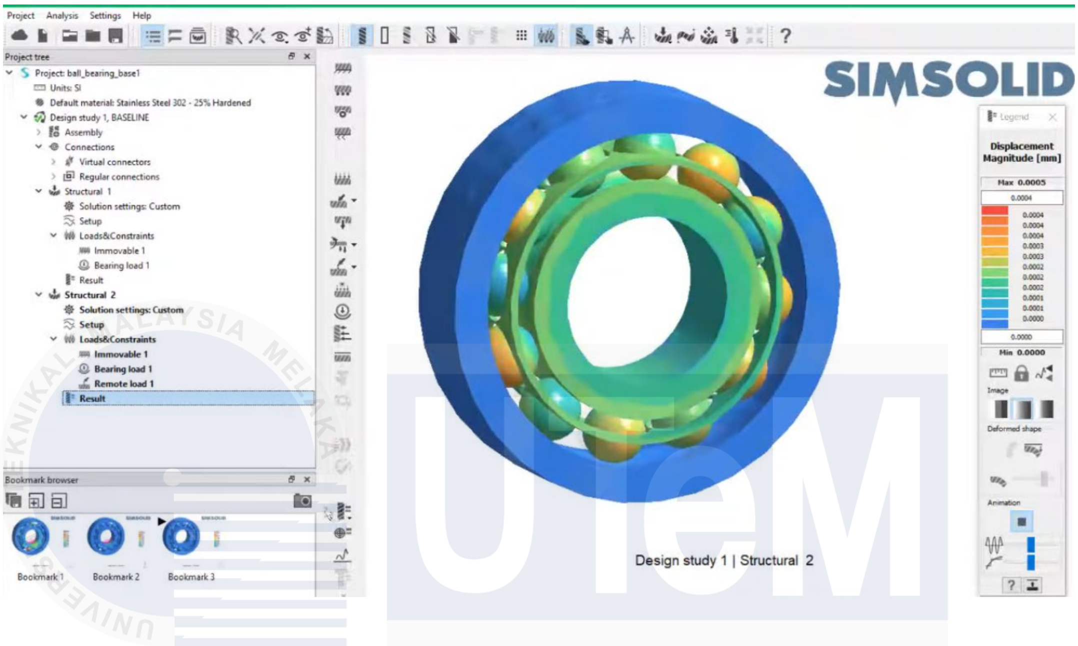


Figure 3.5 Interception and Overlap Results

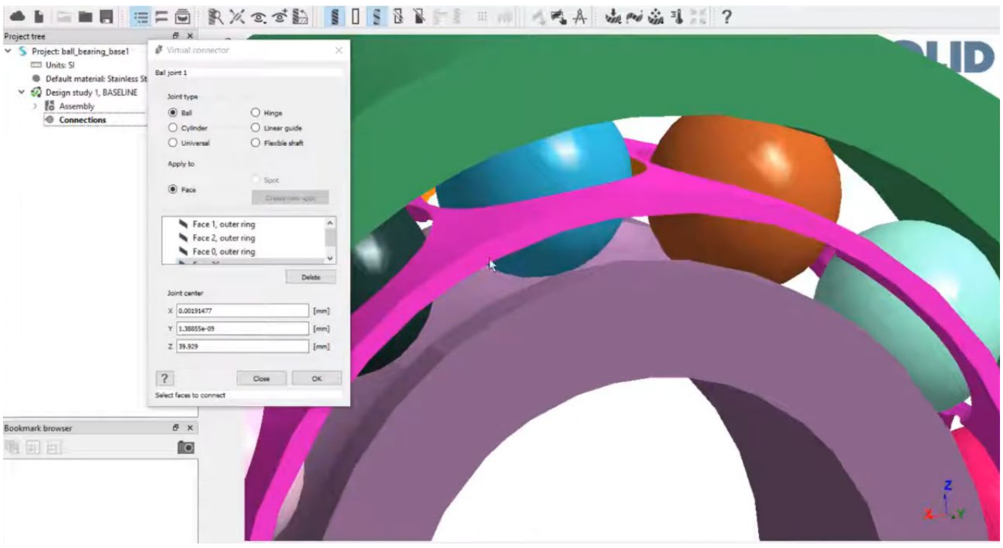


Figure 3.6 Create and Set Up the Connections

I then assigned material properties to each component in the CAD models and performed a Non-Linear Structural Analysis to predict the performance. The outer ring was constrained, while the inner ring was modeled with hinge and rotational inertia characteristics. Furthermore, sliders were added to both the outer and inner rings to allow easy adjustment and movement.

Finally, all analyses were conducted to record reaction and contact forces, as well as system responses. The collected data served as a reference for further optimization.

3.5 Method of Fabrication Process

The manufacturing process utilized SLS 3D printing to produce the newly designed bearing. Selective Laser Sintering (SLS) built the 3D object by sintering powder particles with laser light. This section explained the equipment and procedure used in the fabrication process.

The SLS 3D equipment, central to the process, consisted of a third-generation SLS printer that created 3D objects by depositing layers of powdered material. A build chamber controlled the temperature for optimal sintering. The laser system selectively fused the powder according to the digital design, while a scanning system directed the laser beam path. Preheating units and cooling systems ensured material stability, and control software managed all steps of the printing process.

The operation setup involved three main stages: pre-process, 3D printing, and post-process. The feeder chamber, construction chamber, collector chamber, and powder overflow chamber with a leveling roller were integral to this process (Figure 3.11). The volume and weight of the substance were measured initially, and key parameters were calculated for the printer. During post-processing, the material block was sieved to remove excess powder.

Nitrogen Generator

Farsoon SS402P

Powder Breakout Station

Powder Mixer Machine

Blasting Machine

Personal Protective Equiment

Figure 3.7 SLS 3D Printing Equiment

3.5.1 Method of Printing Process

The three stages of the operation setup pre-process, 3D printing, and post-process were carried out systematically. Feeder, construction, and collector chambers, along with a powder overflow chamber and leveling roller, were used. Measurements of substance volume and weight informed the initial parameters for the printing process. Post-processing involved sieving the material block from the build chamber to ensure a refined product.

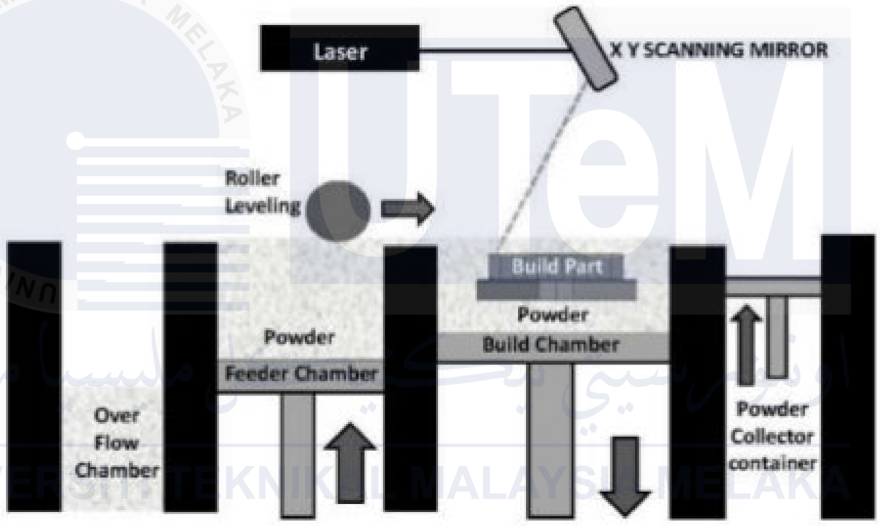


Figure 3.8 SLS Process for Farsoon FS402P, source (Rafi, 2022)

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter focuses on explaining and discussing the results obtained from the SimSolid analysis and fabrication processes. To make the evaluation clearer and more accessible, the findings from the SimSolid analysis are organized into a structured ranking system. By presenting the results hierarchically, it becomes easier to compare the performance metrics of the analyzed designs and gain a better understanding of their relative strengths and weaknesses.

Additionally, by incorporating insights from the fabrication process, this chapter provides a well-rounded evaluation of the designed components. This approach not only highlights the efficiency and practicality of the designs but also simplifies the interpretation of complex findings. The goal is to ensure the data is presented in a way that supports informed decision-making throughout this study.

4.2 SIMSOLID Simulation

This section showcases the simulation results for different suspension component designs, including Solid, Circle, Rectangle, Square, and Triangle configurations, as seen in Figures 4.1 to 4.5. These simulations offer a clear visual insight into how each design handles contact forces and structural responses. By bringing all this data together, we can streamline the analysis and make the decision-making process more straightforward and efficient.

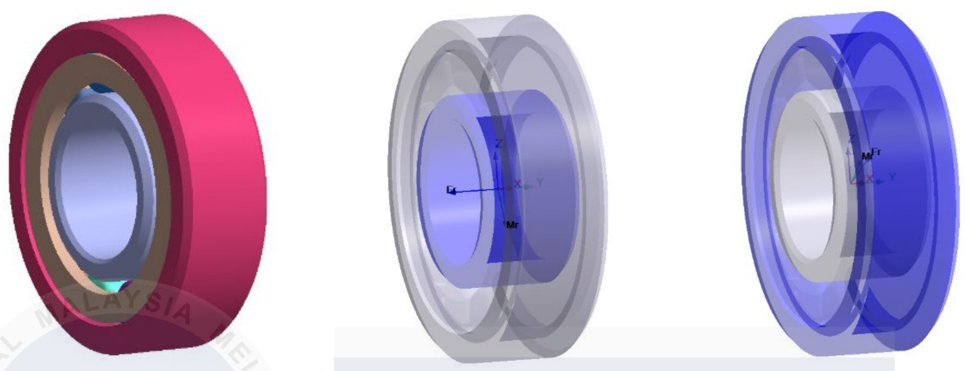


Figure 4.1 SIMSOLID Simulation Results for Solid Design

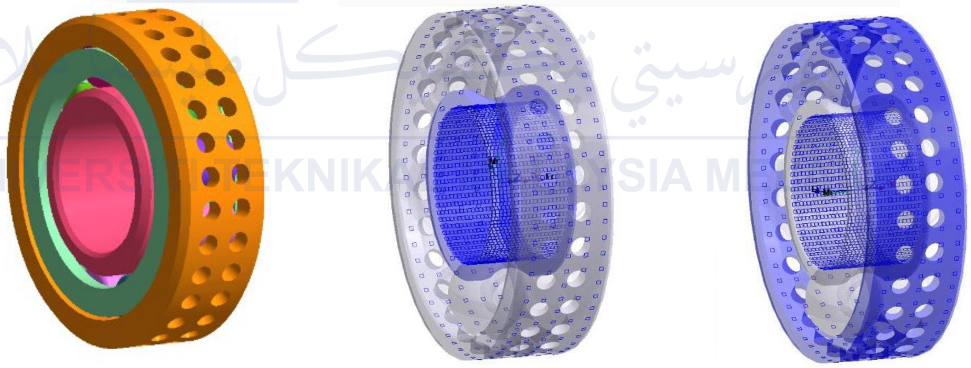


Figure 4.2 SIMSOLID Simulation Results for Circle Design

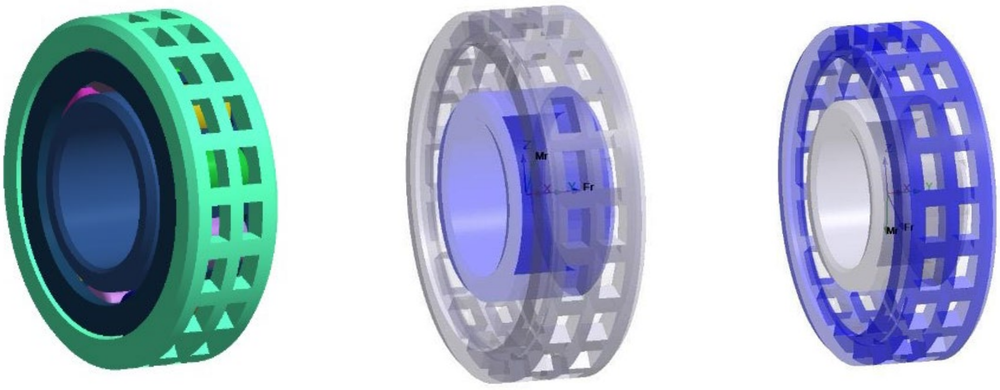


Figure 4.3 SIMSOLID Simulation Results for Rectangle Design

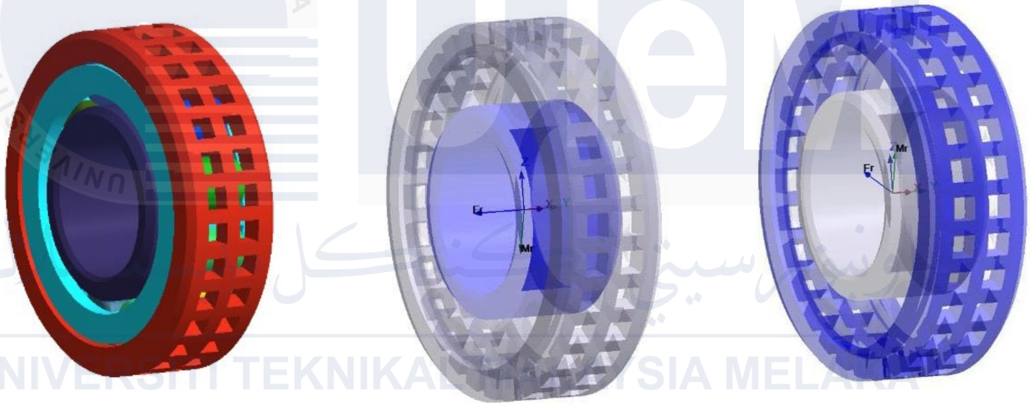


Figure 4.4 SIMSOLID Simulation Results for Square Design

Figure 4.5 SIMSOLID Simulation Results for Triangle Design

This section brings together all the data related to contact forces and responses for the different components that were analyzed. By consolidating this information, the subsequent analysis and decision-making process becomes more streamlined (as shown in Table 4.1). To further enhance understanding, Table 4.2 ranks the components based on their performance metrics, as detailed in Table 4.1. The components are ranked on a scale from 1 to 5, ensuring consistent evaluation. If two or more components achieve the same score, their final ranking is determined by evaluating their performance stability. This method ensures that even closely matched results are fairly assessed.

To reinforce the reliability of these findings, it's worth noting that Altair's official documentation confirms that SIMSOLID aligns with industry-standard reference solutions across a broad range of problem scenarios. This validation underlines the accuracy and dependability of the simulation outcomes presented in this study.

Table 4.1 Overall Simulation Results

Part	**Solid**	**Circle**	**Rectangle**	**Square**	**Triangle**
Max. Displacement Magnitude (mm)	4.88E-07	5.08E-07	5.32E-07	5.08E-07	5.156E-07
Force (N) – Outer Ring Cage	7.64E-05	1.497E-05	2.25E-05	1.13E-05	2.25E-05
Force (N) – Ball Cage	7.62E-05	1.534E-05	2.25E-05	3.26E-06	7.86E-05
Force (N) – Inner Ring	3.96E-06	1.49E-06	1.86E-06	3.26E-06	2.25E-06
Moment (Nm) – Outer Ring	9.88E-09	1.41E-08	1.45E-08	7.63E-09	1.45E-08
Moment (Nm) – Ball Cage	1.27E-08	1.89E-09	1.22E-08	2.94E-09	2.68E-09
Moment (Nm) – Inner Ring	1.07E-08	2.05E-08	2.68E-09	1.06E-08	1.22E-08

Table 4.2 Overall Ranks

Part	Solid Rank	Circle Rank	Rectangle Rank	Square Rank	Triangle Rank
Max. Displacement Magnitude (mm)	1	2	5	3	4
Force (N) – Outer Ring Cage	4	3	5	1	5
Force (N) – Outer Ring Cage	4	3	5	1	5
Force (N) – Inner Ring	3	1	2	4	5
Moment (Nm) – Outer Ring	4	3	2	1	2
Moment (Nm) – Ball Cage	5	1	4	2	3
Moment (Nm) – Inner Ring	3	4	5	2	1

Table 4.3 Cumulative Scores

Geometry	Cumulative Score	Overall Rank
Solid	28	3
Circle	28	3
Rectangle	27	1
Square	28	3
Triangle	28	3

The simulation results provide valuable insights into how different geometries—sSolid, Circle, Rectangle, Square, and Triangle—affect the performance of ball thrust bearings. Among these, the Rectangle emerged as the best all-around performer, earning the highest overall ranking. This is because it delivered steady, reliable results across all categories, even though it didn't always take the top spot in individual metrics.

The Square geometry showed impressive results in reducing forces and moments, particularly on the outer ring cage and ball cage, which makes it highly efficient and stable. However, its performance dipped slightly in a few areas, affecting its overall score. Similarly, the Circle geometry performed well, especially in reducing forces and moments, but it fell short in other aspects like displacement, which lowered its final ranking.

The Solid and Triangle geometries, while functional, struggled with higher forces and moments in key areas, making them less efficient compared to the other designs. Even so, these geometries may still have specific applications where their strengths can shine.

Overall, the Rectangle proved to be the most well-rounded design, combining balance and reliability. The Square and Circle geometries, on the other hand, excelled in certain key areas, making them strong contenders depending on the application. These results help us understand how geometry affects bearing performance and point toward future improvements for better efficiency and stability.

4.3 Fabrication Defects

The fabrication process encountered numerous challenges, primarily stemming from the use of recycled Nylon PA12 powder and certain inefficiencies in the 3D printing equipment. Significant issues such as uneven sintering, porosity, and inconsistent layer adhesion were observed in the components produced. These defects were closely tied to the inherent material properties of recycled PA12 and the technical limitations of the machinery employed.

Recycled PA12 powder, compared to virgin material, often exhibits reduced thermal consistency and flowability. These characteristics can lead to non-uniform sintering and weaker structural integrity in the printed components. Beyond material-related factors, equipment issues also played a significant role. Temperature fluctuations within the build chamber and occasional misalignment of the laser system contributed to the defects, manifesting as irregular surfaces, minor warping, and diminished mechanical strength. In particular, unstable chamber temperatures resulted in incomplete sintering in certain areas, while the misaligned laser paths created uneven bonding between layers.

Figure 4.6 Outer bearing **cracking** using recycled powdered Nylon PA12

Addressing these issues requires a multifaceted approach aimed at both the material and the equipment. Adjusting critical machine parameters, such as laser power, scan speed, and chamber temperature, is essential to better accommodate the properties of recycled PA12. Such optimization would enable more consistent sintering and improved bonding between layers. Enhancements to the preparation of recycled PA12 powder are equally crucial. By pre-treating the powder to improve its flowability and thermal performance, issues such as uneven powder distribution and weak adhesion could be mitigated, resulting in more reliable material behavior during the printing process.

Additionally, regular maintenance and calibration of the 3D printing equipment are indispensable. Properly maintaining the machine would address the inconsistencies caused by temperature fluctuations and laser misalignment, ensuring more accurate and defect-free fabrication.

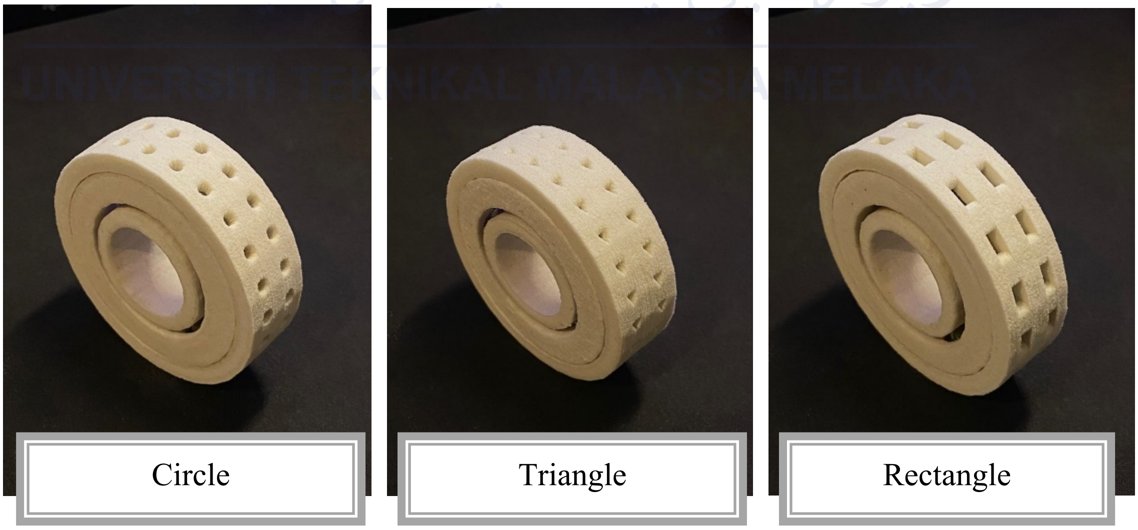
By focusing on these improvements, it is possible to significantly reduce defects and enhance the overall precision and reliability of the manufacturing process. This analysis underscores the critical need to address both material-related and equipment-related limitations to achieve higher-quality components with consistent performance.

4.4 Design Adjustments for Prototyping

Another challenge was adjusting the width of the prototype design to suit the 3D printing process and the properties of recycled PA12. These adjustments were necessary but did not match the original design measurements.

This happened because the fabrication process often changes dimensions due to shrinkage, thermal expansion, or uneven material distribution. These effects are more unpredictable with recycled PA12. To maintain the prototype's integrity and functionality, some changes in design dimensions were needed. For example, increasing the width of certain features helped offset shrinkage and achieve the correct final dimensions. However, excessive adjustments could affect accuracy and deviate from the original design intent.

Figure 4.7 Final Prototype Fabricated Using Recycled PA12 Powder



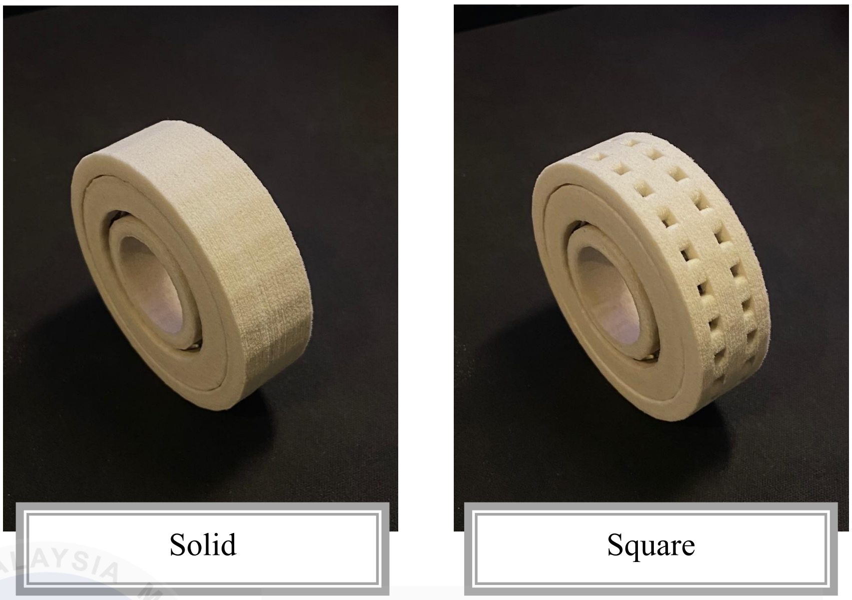


Figure 4.8 Final Fabricated Hybrid Bearing Geometries

To handle this issue, it's important to use design-for-manufacturing (DFM) principles tailored to 3D printing with recycled PA12. These include accounting for shrinkage rates, using simulations to predict dimensional changes, and adding tolerances to the design. Iterative prototyping and testing are also essential to fine-tune the design and ensure it meets specifications.

By following these strategies, design adjustments can be minimized, and the prototype can better match the original design. This shows how important it is to consider manufacturing constraints during the design phase to get the best results in 3D-printed parts.

CHAPTER 5

CONCUSSION AND RECOMMENDATION

5.1 Conclusion

This study set out to develop and assess optimized components fabricated using polyamide PA12 powder through advanced 3D printing techniques. By combining SIMSOLID simulations with precision fabrication methods, we gained a comprehensive understanding of the components' performance. The designs were created using CATIA V5 and evaluated for their behavior under contact forces and responses. Although challenges arose during the fabrication process, the study provided valuable insights into both the design and manufacturing aspects.

Despite some defects in the final components, such as porosity, uneven adhesion between layers, and incomplete sintering, the experimental evaluation demonstrated promising performance. These issues, which were linked to both the material properties and limitations of the equipment, underscored the need for further optimization. However, the findings reinforced the potential of PA12 powder in creating functional components, provided machine parameters are fine-tuned for better consistency.

Through the combination of simulation data and experimental results, this study emphasized the importance of precision in both design and fabrication. The results offer a practical roadmap for improving manufacturing outcomes, showing that sustainable and high-performance materials can be used successfully when the process is optimized.

5.2 Recommendations

For future improvements, the study suggests a few key areas for refinement. First, enhancing the pre-treatment of PA12 powder would improve its thermal consistency and flowability, ensuring better sintering and fewer defects. Adjusting the machine settings such as laser power, scan speed, and build chamber temperature can also significantly improve the quality of the components.

Moreover, regular maintenance and calibration of the 3D printing equipment are crucial to minimize defects caused by issues like temperature fluctuations and laser misalignment. Implementing real-time defect monitoring could further enhance the fabrication process by offering immediate feedback, helping to improve consistency and quality in the components.

Looking ahead, it would be valuable to explore a wider range of materials, including different polymers or metals, to compare performance across various designs. This would provide deeper insights into how different materials behave and help optimize designs for specific applications.

5.3 Future Prospects

This research highlights the importance of sustainable materials and advanced manufacturing methods in modern engineering. While challenges did arise from the use of PA12 powder, this study has demonstrated its potential to produce durable, high-performance components. The use of detailed simulations like SIMSOLID has shown how we can analyze and optimize designs in a precise manner, offering a pathway to more efficient and environmentally-friendly production processes.

Future work should focus on overcoming the material and equipment limitations identified here. Innovations in material science, such as new additives to enhance the properties of recycled powders, as well as advancements in additive manufacturing technologies (such as adaptive laser systems), could help address these challenges.

By adopting these improvements and expanding research into new materials and applications, the findings from this study have the potential to shape the future of manufacturing. These advancements will lead to more reliable, sustainable, and cost-effective production processes, meeting the needs of industries as they evolve.

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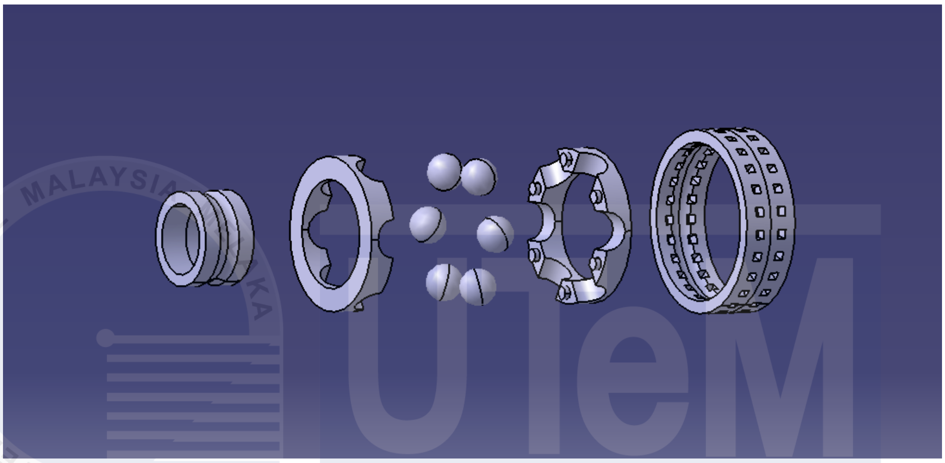
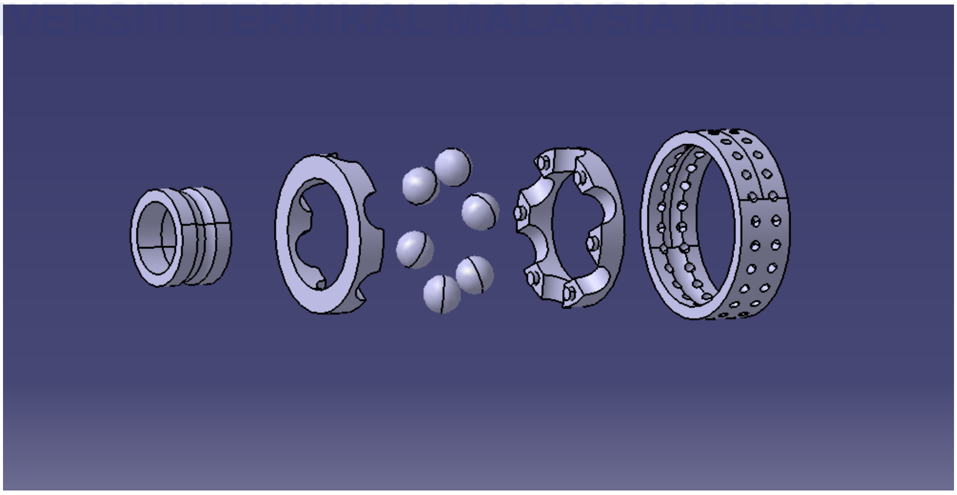
APPENDICES

APPENDIX A – Designed Hybrid Bearing with Geometry

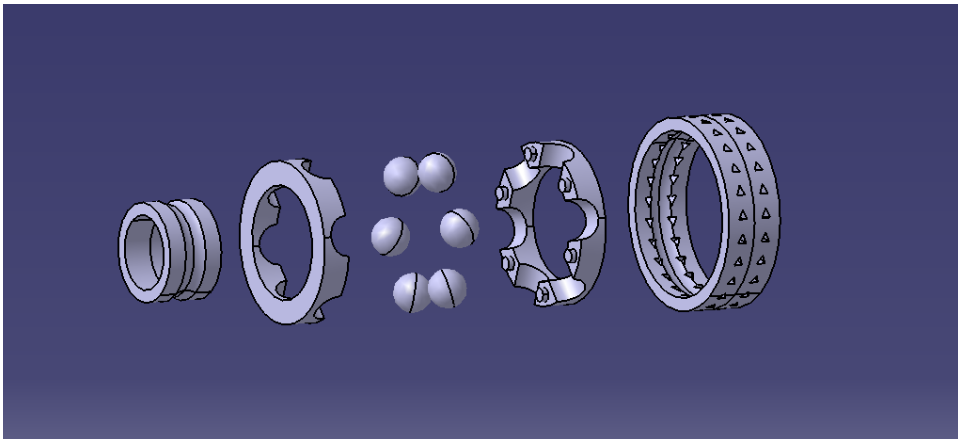
Square Design



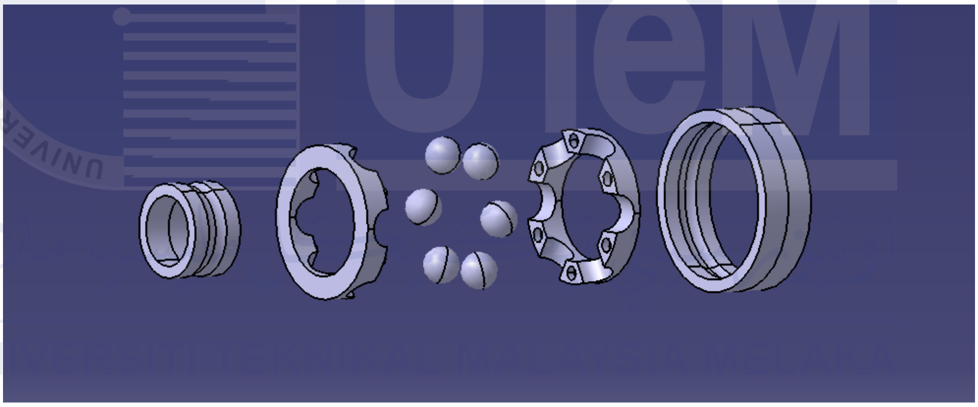
Circle Design



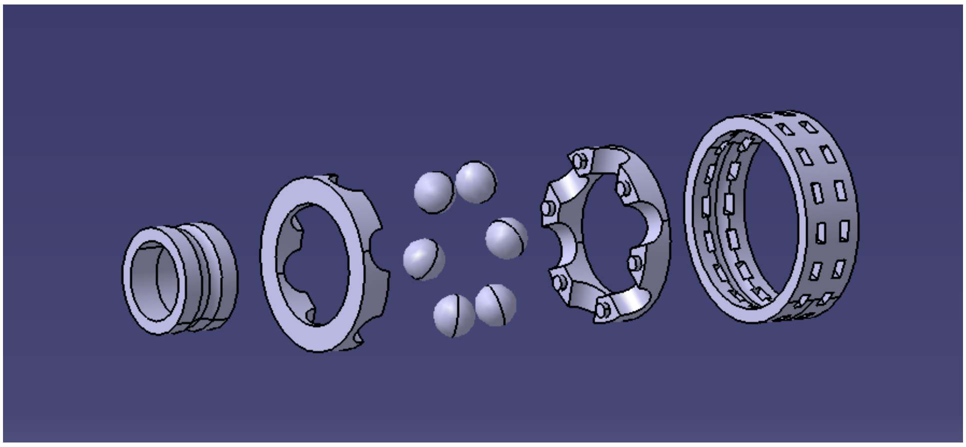
Triangle Design



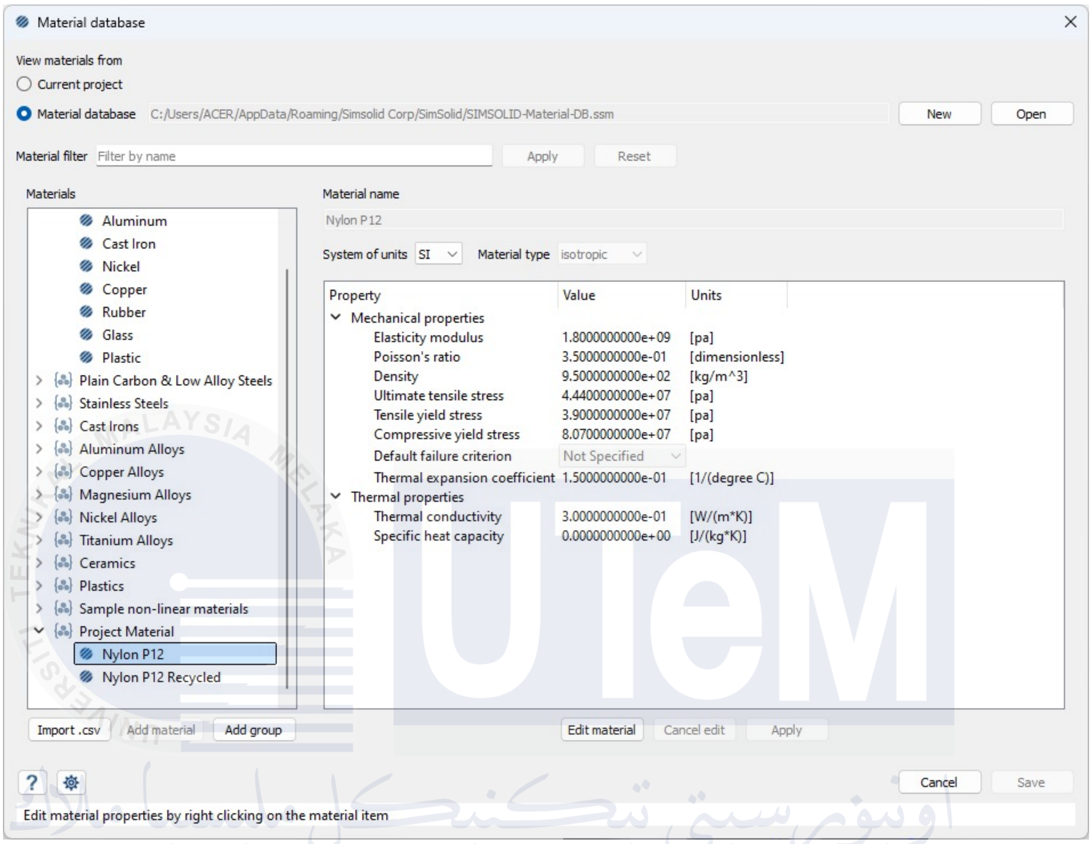
Solid Design

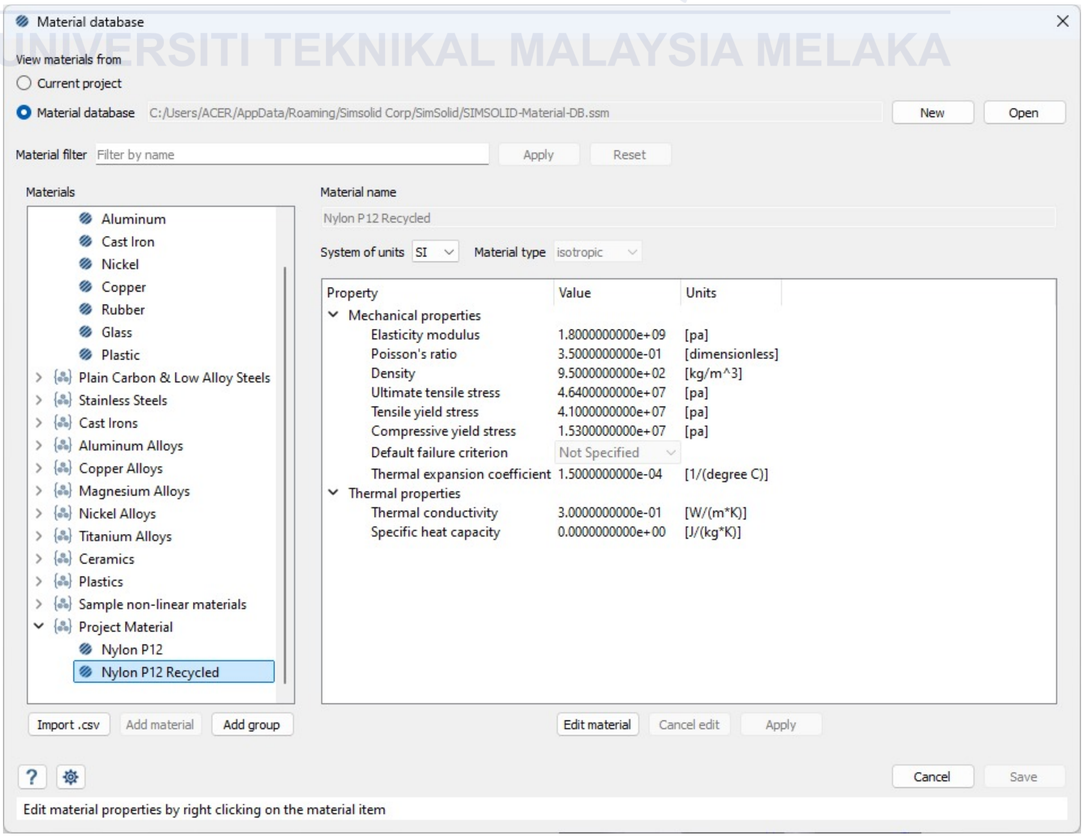


Rectangle Design



APPENDIX B - Customized Material Properties for Nylon PA 12 in SIMSOLID





APPENDIX C – Processed Fabricated Prototype Hybrid Bearing