Development of Lead-free PTFE Based Sliding Bearing Materials

By

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To my parents

Abstract

A group of novel polytetrafluoroethylene (PTFE) based composite materials are developed for sliding bearing applications. The reinforcements include the newly developed T-401 Tribaloy alloy, which possesses better ductility than conventional Tribaloy alloys, spherical bronze particles, milled graphite and chopped carbon fibers. The specimens are fabricated with the compression moulding technique under different preforming and sintering cycles. The mechanical and tribological properties, and also the corrosion resistance to acid of the new composites are investigated with immersion density, durometer hardness, tensile, pin on disk and immersion corrosion tests, respectively. It is demonstrated that the wear resistance of all developed PTFE composites is much higher than that of pure PTFE, while the composites maintain the extremely low coefficient of friction of PTFE. Among the developed composites, the mixture of 40% PTFE + 15% T-401 + 45% bronze has the best combination of properties. Capable of working properly in different lubrication regimes and being much softer than lead-containing bearing materials, the composite has superior compatibility, conformability and embeddability to existing sliding bearing materials. This new material exhibits a yield strength of about 15 MPa, which is 50% higher than the best reported yield strength of existing PTFE composites, and the load capacity of this composite is comparable to that of lead-base babbitts. As a potential new generation of sliding bearing materials, the developed composite with cost-effective and corrosion-resistant features maintains the excellent antifriction property of PTFE, while its wear resistance is improved by one order of magnitude.

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Nomenclature

PTFE	Polytetrafluoroethylene
HIP	Hot isostatic pressing
SEM	Scanning electron microscopy
ASTM	American society for testing and materials
MTS	Material testing system
ASM	American society for metals
TFE	Tetrafluoroethylene
PAN	Polyacrylonitrile
FCC	Face centered cubic
HCP	Hexagonal close packed
MSDS	Material safety data sheet
μ	Coefficient of friction
σ_Y	Yield strength
σ_{ULT}	Ultimate strength
σ_F	Tensile strength at break
El	Elongation
E	Young's modulus

Chapter 1: Introduction

1.1 Background and Significance

Friction is defined as the resistance to the sliding of one solid body over or along another body that tends to oppose the relative motion of two surfaces in mechanical contact [1]. The causes for the generation of this resistance, which commonly occurs in machinery, include a set of microscopic interactions between the moving surfaces. These interactions are affected by mechanical, physical, geometrical, and chemical characteristics of the sliding surfaces, their surrounding atmosphere, and overall operational sliding conditions. Friction is desirable in some applications such as mechanical parts that are bolted together. However, in moving machinery, computer hard disk systems, and engines; friction is not desirable since it is responsible for dissipation and loss of much energy [1, 2].

In order to reduce friction, lubricants are commonly introduced between two moving surfaces. In the meanwhile, various devices have been designed for and employed in machinery. Bearings are typical devices utilized to control friction by separating the moving surfaces. These devices permit constrained relative motion between two parts in mechanical applications such as jet and automotive engines. There are two types of bearings; namely, rolling bearings and sliding bearings. In rolling

bearings loads are carried by rolling elements and sliding friction is almost avoided. However, in sliding bearings loads are carried via sliding actions and predominantly sliding contact occurs between relatively moving surfaces.

Although friction becomes lower by the usage of bearings in mechanical devices, it is not generally as low as it is desirable to be. When two surfaces are in contact with each other, the real mechanical contact area consists of a number of small local asperities. Therefore, the real contact area is much smaller than the nominal contact area that results in unacceptable friction and surface damage [1]. Thus, a variety of liquid lubricants including oil, grease, and water are simultaneously used with bearings to effectively lessen the friction and allow easier sliding. Three different lubrication regimes in bearings are [1]:

- Thick-film lubrication: Also known as hydrodynamic lubrication, refers to the complete separation of contacting asperities by a fluid lubricant film. In this regime, the entire load is supported by the lubricant pressure.
- Boundary lubrication: In this lubrication regime, the load is totally borne by asperities. Friction behavior in boundary lubrication is governed by any planned or unplanned film that happens to be on the surface.
- Thin-film lubrication: A mixed lubrication regime in which part of the load is supported by the fluid pressure and the rest is carried by contacting asperities.

In sliding bearings, predominantly sliding contact occurs between relatively moving surfaces and the need to employ a lubricating agent is much more than that of a

rolling-element bearing since friction generation is significantly more in a sliding motion compared to a rolling motion [1]. While efficiently control the system friction, liquid lubricants have usage difficulties for many reasons. These difficulties include:

- Design problems: Liquid lubrication sometimes requires complicated housing design with need for oilways or lubricant nipples that increases the overall cost.
- Accelerated corrosion: Normal lubricating agents cannot be used in hostile environments due to the harsh resultant corrosion damages.
- Environmental considerations: Strict regulations for using lower oil flows and disposal of lubricants must be met to avoid any damages to the environment.
- Operational problems: Most of the lubricants can be used in very limited operational temperatures. Also, relubrication is a difficult and time consuming process and sometimes impossible for the parts that are inaccessible after assembly. In addition, in start up and shut down conditions, severe damages may occur under boundary or partial boundary lubrication conditions.

As a result, there was a strong desire among bearing designers to produce sliding bearings that successfully reduce friction without employing any liquid lubricants. This desire promoted the development of self-lubricating sliding bearings, which are independent of external liquid lubrication. In these types of bearings, liquid lubricants are replaced by self-lubricating materials. Self-lubricants are any solid materials that show low friction without application of liquid lubricants. Graphite, molybdenum disulfide (MoS_2), and boron nitride (BN) are the predominant materials used as solid lubricants. These materials are introduced between two rubbing surfaces for the purpose of reducing

friction and providing protection from damages that may happen during relative movement.

Lead (Pb) is a solid lubricant which is widely used in sliding bearings with mixed lubrication regimes. For many years, various types of lead-base and lead-containing sliding bearings have been being used due to the excellent lubricity, good antiseizure characteristic, wide operating temperature capability, satisfactory embeddability, good corrosion resistivity, and low cost of lead [3]. However, because of its inherent toxicity, lead must be removed from bearings according to the global environmental legislation.

Due to their excellent characteristics such as low cost, good lubricity, low weight, and high corrosion resistivity; many polymers including nylon, acetal, and polyethylene are used as bearing materials and may be good replacements for the conventional lead-based bearing materials. Among polymeric materials, polytetrafluoroethylene (PTFE), which is a synthetic fluoropolymer, is considered as a remarkable solid lubricant. Exhibiting the smallest coefficients of static and dynamic friction of any known solid material, PTFE has been widely used as a self-lubricant. While showing excellent antifriction properties, PTFE suffers from a high wear rate that greatly limits its application [1]. Wear is defined as “the progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface” according to the ASM handbook [1]. Sliding wear then refers to a type of wear generated by the sliding of one solid surface along another surface. Improvement in the PTFE wear resistance is

significantly important since it will result in high durability of sliding bearings, and improvement in performance, integrity, and reliability of the entire engineering system.

Considerable efforts [4-7] have been made to reduce such type of wear damage by developing PTFE composites. In these types of composites, PTFE was used as the thermoplastic resin matrix that was incorporated with many types of additives including organic and inorganic fillers as reinforcements. However, the properties of these composite materials are not comparable to those of conventional lead-containing bearing materials [1]. In addition, much of the presented data give insufficient information about the exact pedigree of the constituents and the fabrication history of the composites [4-7].

Although the choice and fraction content of the fillers can affect the final properties of a composite material, other factors such as size, shape, aspect ratio, and hardness of the fillers; as well as composite fabrication technique may complicate the situation [1, 2, 8, 9]. Furthermore, while various PTFE composites were studied extensively in the past, many contradictory data were reported in literature. Also, the published data are not comparable to each other since a standard guide in developing PTFE composites and reporting their properties was not available until recent years [5, 6, 10]. For these reasons, bearing manufacturers were not convinced to replace lead-based bearings with existing PTFE composites. Therefore, it was proposed to revisit PTFE materials to design a suitable sliding bearing material whose properties are comparable or superior to those of existing lead-containing bearing materials.

1.2 Objectives and Methods

The present research is a joint project between Carleton University and National Research Council Canada (NRC), sponsored by an NSERC Collaborative Research and Development Grant (CRD). The industrial collaborators are Deloro Stellite Inc., Canadian Babbitt Bearings Ltd., and Pratt & Whitney Canada. The project is aimed at developing novel PTFE based composite materials for sliding bearing applications with a newly developed cobalt-base Tribaloy alloy (T-401). The previous research has demonstrated that T-401 maintains the excellent wear and corrosion resistance of conventional Tribaloy alloys such as T-400 and T-800, while its ductility becomes much improved [11]. It is expected that this new alloy find new application in sliding bearing materials in order to increase wear resistance.

Also, to ensure the developed composites are wear resistant and can run equally well under different lubrication regimes, bronze and graphite were respectively added. The former as a metal with high thermal conductivity can improve the ability of PTFE to effectively dissipate the heat generated during the bearing operation while the latter as a solid lubricant imparts better dry lubricity. In addition, carbon fiber was used to improve the load carrying capability and thermal conductivity of PTFE.

It is expected that the newly developed PTFE composites possess superior wear and corrosion resistance as well as superior mechanical properties to existing PTFE based sliding bearing materials. Also, the new composites are expected to become the replacements for existing lead-containing bearing materials such as lead-base babbitts,

which has a soft lead matrix and harder reinforcing particulates, owing to comparable or superior mechanical, tribological, and anti-friction properties. The significance of this research lies in the application of scientific methods to an important class of industrial materials having significant practical value, and also in the development of environmentally compliant materials whose use will promote a clean and health-sustaining work place and environment. Therefore, this work will create both industrial and economic benefits as well as social benefits.

The following tasks are involved in this research, consisting of two main parts: specimen fabrication and material characterization.

Part I: Specimen fabrication

1. Determination of chemical compositions: The matrix material for the developed composites is PTFE powder and the fillers include Tribaloy alloy T-401, spherical bronze particles, milled graphite, and chopped carbon fibers. In order to investigate the effects of these reinforcements and their contents on the properties of the PTFE composites, the specimens are made with different combinations of the fillers at different content levels.
2. Preparation of powders: To overcome the heterogeneous mixing of the powders, all the powder form raw materials are screened with a sieve # 12 (1.68 mm sieve size) prior to the mixing step to get fluffy powders.

3. Mixture of powders: Fillers are mechanically mixed in a three dimensional mixer. Mixing step is split into two separate stages. In the first stage, the fluffy powders are mixed for 45 minutes. After that, the mixed powders are screened by sieve # 18 (1 mm sieve size) and any lump is broken up. Afterward, the mixture is put in the mixer again for 30 minutes.
4. Compression moulding/sintering process: Compression moulding technique is used to fabricate pure PTFE and seven different PTFE-based composites.
5. Sintering/HIPing process: Hot isostatic pressing fabrication technique is also tested.

Part II: Material characterization

1. Microstructure analysis: Microstructural analysis of the specimens is performed using light microscopy and scanning electron microscopy (SEM) techniques.
2. Density test: The density of each specimen is measured using immersion density technique.
3. Corrosion test: Immersion testing method is used to evaluate the corrosion resistance of the specimens according to the ASTM Standard G 1 – 03 [12].
4. Hardness test: Hardness of each specimen is assessed with a Durometer hardness tester according to the ASTM Standard D 2240-05 [13].

5. Tensile test: Mechanical properties of the specimens are determined using a MTS system in accordance with the ASTM Standards D 4894-04 [13], D 4745-06 [15], D 1708-06a [16], and D 638M [17].
6. Wear test: A computer controlled pin-on-disk tribometer is employed to evaluate the wear resistance of each specimen in accordance with ASTM Standard G 99-05 [18]. The worn surfaces of all the specimens are examined using optical and SEM microscopy techniques.
7. Friction test: The coefficient of friction (μ) of each specimen is automatically recorded throughout the wear test with the aid of a linear variable displacement transducer.

1.3 Construction of the Thesis

The thesis consists of six chapters as described below:

Chapter 1 is an introduction to this project, which describes the background and significance, as well as the objectives and methodologies of this research.

Chapter 2 is literature review of the previous researches related to the current project.

Chapter 3 describes the details of the specimen fabrication methods and procedures such as moulding and sintering processes.

Chapter 4 describes the experimental details such as microstructural analysis, mechanical tests, tribological tests, and corrosion test.

Chapter 5 presents the experimental results and discussion.

The conclusions drawn from this research are given Chapter 6, also with the recommendations for future work.

Chapter 2: Literature Review

2.1 Sliding Bearings

2.1.1 Types of bearings

Bearings are typical tribological components used to reduce friction or restrain linear or rotational motion between two mechanical parts. The friction reduction mechanism of a bearing may be through a combination of factors. These factors include bearing's specific shape, material, or separation of mechanical parts by exploiting a fluid layer (lubricant) or electromagnetic field [19]. In general, there are two major types of bearings: rolling-element bearings in which the rolling friction principle is employed; and sliding bearings in which the principle of sliding friction is utilized.

A rolling-element bearing is a device with round elements by which the load between two moving parts is supported. The round elements roll due to the relative motion of the moving parts; thus, there is little or no sliding motion in these types of bearings. Therefore, friction generation and lubricant dependency in rolling bearings are less compared with other types of bearings [2]. There are many kinds of rolling-element bearings. Considering the geometry of the rolling elements, these bearings can be classified into two main categories: ball bearings, as shown in Figure 2.1 and roller

bearings, as shown in Figure 2.2. The former employs spherical (ball) rolling elements while the latter uses cylindrical rolling elements [20].

Figure 2.1 A single-row radial ball bearing (Courtesy of SKF Bearing Industries Co.)

Figure 2.2 A single-row radial roller bearing (Courtesy of SKF Bearing Industries Co.)

A sliding bearing, as shown in Figure 2.3, is a bearing in which the load is carried via a sliding action and it is usually used for rotary shafts. Sliding bearings normally consist of two elements so that these bearings are lightweight, inexpensive and easy to repair. The elements in a typical axial sliding bearing can be two plane surfaces. Also, in a radial sliding bearing, the elements are a rotating shaft inserted into a hollow part [21].

Figure 2.3 A radial spherical plain bearing (Courtesy of WYKO Co.)

In sliding bearings used for rotating shafts, two terms are commonly used: plain bearing (also called bushed bearing or bushing) and journal bearing. Plain bearing term refers to the cases where the shaft and original hub are fixed. The term journal bearing or sleeve bearing is used when the shaft and hollow element are not tightly attached and move relative to each other [2].

There are four major types of sliding bearings [22]:

1. **Film-lubricated bearings:** the normal sliding bearings, which are usually lubricated by either oil or grease.
2. **Dry-rubbing bearings:** also called self-lubricating bearings, which have slippery working surfaces such as PTFE or graphite. These bearings can work with or without lubrication.
3. **Solid lubricant-impregnated bearings:** the bearings made from a matrix impregnated with a solid lubricant such as graphite or molybdenum disulfide. These bearings are also capable of working in the presence or lack of lubricating agents.

4. **Pre-lubricated bearings:** a composite with a porous matrix such as sintered powder bronze powder impregnated with lubricating oil.

2.1.2 Failure modes of sliding bearings

Premature failure in sliding bearings can cause a lot of problems; therefore, slow or sudden failure prevention is a major issue in sliding bearing design. Main damages, which lead a sliding bearing to failure mode, include [23]:

1. Severe scoring of the bearing surface in direction of motion due to the presence of dirt particles in lubricant
2. Cavitation erosion caused by inadequate lubrication design
3. Corrosion because of the improper material selection
4. Bearing seizure due to the entrapment of undesirable particles between the bearing and housing
5. Loss of lining because of inaccurate lining technique
6. Bearing surface melting due to the overheating problem caused by excessive load or insufficient lubricant supply
7. Uneven wear caused by bearing misalignment or imbalance shaft
8. Cracking and crack propagation because of fatigue problem caused by excessive dynamic loading

To extend the service lives of the bearings, the materials used for sliding bearings should somehow minimize these damages.

2.2 Sliding Bearing Materials

Sliding bearings are made from a variety of materials. The main purpose of bearing material selection is the production of a bearing with smooth operation and long lifespan. The selection of proper materials depends upon several factors. Final application is a very important factor. For example, some materials are suitable for high or low temperature applications. Others may be good for harsh and corrosive environments or the cases with high vibration [2]. Also, operating factors such as sliding velocity of bearings (elevated or low speed) and the load that must be carried by bearings are some other key factors that should be considered by bearing designers. In addition, dry-running applications may need self-lubricating materials, while the presence of lubricating agents can give bearing designers more options in material selection.

2.2.1 Selection criteria

A set of criteria has been developed for use in evaluating the quality of sliding bearing materials. However, it is really hard to find a bearing material with equally good properties with respect to all criteria. Therefore, a proper selection of sliding bearing materials is totally dependent on the final application of the bearing and it is also a compromise between the different conflicting criteria. In general, the following eight main criteria should be used when selecting sliding bearing materials:

1. **Compatibility:** the anti-weld and anti-scoring abilities of a bearing. Self-lubricating bearings and bearings operating with full film lubrication may sometimes operate with boundary or no lubrication conditions. As a result, localized welding spots can be generated due to the high produced friction.

This localized welding spots can cause a seizing damage that is similar to the scoring. Thus, bearing materials should be chosen considering asperity (shaft) materials to avoid any possibility of localized welding during the dry-running conditions. For instance, cadmium-base bearings are among the good choices against steel shafts regarding compatibility [2, 24].

2. **Conformability:** the ability of a bearing to conform itself to any geometric errors including misalignment and deflection. Among metallic compounds, a softer material, which generally has a lower modulus of elasticity, exhibits better conformability properties [24].
3. **Embeddability:** a measure of undesirable particle absorption of a bearing. The undesirable particles could be any foreign particles such as lubricant impurities, or even the debris produced during the bearing operation. Babbitts are considered as embeddable bearing materials since they are able to bury hard foreign particles in their soft surface to avoid any possible shaft damage [2].
4. **Load capacity:** the maximum unit pressure under which the material can operate without excessive friction or wear damage. Although bearing design and presence of lubricating agents can alter the load capacity of a bearing, proper selection of the bearing materials has a significant effect on the bearing's load capacity. Bronze bearings are examples of bearings with good load capacity [1, 2].

5. **Functionality:** a measure of anti-friction and anti-wear ability of a bearing. A functional bearing such as a lead-containing bearing can reduce the friction considerably, while it does not suffer from wear during operation [2, 24].
6. **Fatigue resistance:** the ability of a bearing material to withstand properly in cyclic loads. This ability is considered as an important attribute for bearings used in aircraft and automotive industries. Bronze, silver, and aluminum can endure cyclic loads more than babbitts because of their higher hardness and strength compared with babbitts [2, 24].
7. **Corrosion resistance:** a measure of bearing resistivity to corrosion. Some bearing materials are more susceptible to corrosive environments, elevated temperatures, and some lubricating oils. For instance, lead, cadmium, copper, and zinc alloy bearings may be corroded by some lubricating agents. However, the addition of tin to lead babbitts and coating cadmium by indium can improve the corrosion resistivity of the bearings [2, 24].
8. **Overall cost factor:** playing a vital role in the final bearing composition since selection of the proper composition of a bearing in a specific application is not just limited to one choice. For example, in aerospace applications, it might be feasible to use expensive bearing materials. However, in cases where the cost of the final bearings is an important issue, a combination of a low-cost substrate and a high-cost coating can be an effective solution [2, 24].

2.2.2 Categories

Sliding bearing materials can be classified into two major categories: nonmetallic materials and metallic materials. The former is normally used in self-lubricating

applications while the latter is used in oil-lubricating applications. Some of these compounds are lead-containing materials, which will be discussed in another section, while lead-free sliding bearing materials will be introduced in this section.

2.2.2.1 Nonmetallic materials

Many types of nonmetallic materials are used to make sliding bearings. Graphite, molybdenum disulfide (MoS_2), and several types of polymers including PTFE and nylon (polyamides) are among the most widely used nonmetallic sliding bearing materials. For instance, a hybrid of the epoxy polymer and MoS_2 was used by Shiao *et al.* [25] to produce a dry-self lubricating composite. One advantage of these nonmetallic materials is that they generally do not require any liquid lubrication. However, the wear resistance and anti-friction property of a self-lubricating bearing can become significantly improved by the application of any lubricating agents. Another advantage of nonmetallic compounds is that they can remain functional in extremely low or high temperatures whereas conventional lubricants cannot function properly in these conditions.

2.2.2.2 Metallic materials

Sliding bearings can be fabricated using various types of metallic materials. There are five major types of lead-free metallic bearing materials:

1. **Tin-base babbitts:** also known as white metals, considered as one of the best lead-free metallic bearing materials. The conventional composition of these babbitts is either 90% tin with 10% copper or 89% tin with 7% antimony and 4% of copper [2].

2. Lead-free bronze: harder but cheaper than babbitts. Lead-free bronze materials can be classified into three different categories:

- **Aluminum bronze:** a very well known alloy because of its good properties at elevated temperature applications. These properties include high strength, and good wear, creep, and corrosion resistivity. Aluminum bronze alloys may contain up to 14% aluminum in their compositions [2].
- **Manganese bronze:** its strength and hardness are increased by addition of manganese element [2]. As a result, the load capacity of the bearings made with these alloys is higher compared to the simple bronze slider bearings.
- **Sintered bronze:** fabricated by sintering (high temperature) and HIPping (high pressure) processes to make a strong porous material with the powdered bronze. The pores then act as oil reservoir for lack of lubrication conditions since they are impregnated with lubricating agents such as oil, graphite, or PTFE.

3. Aluminum and aluminum alloys: have emerged to market as a substitute for bronze and babbitt alloys. However, the successful application of these alloys is restricted. For instance, in low load and high-speed applications, aluminum alloys cannot work properly. In addition, their embeddability, conformability and compatibility properties are poor. Furthermore, a hardened shaft and improved surface finish is needed for aluminum alloys [1]. Some advantages of aluminum alloys are their low cost, excellent fatigue strength, good corrosion resistance, high load capacity, long life, and good thermal conductivity [24]. SAE 770, SAE 780, SAE 781, zinc-aluminum alloys, and

tin-aluminum alloys are among the most commonly used compositions of aluminum based sliding bearings [2].

4. **Sintered iron:** a cheaper replacement for sintered bronze bearings. Sintered iron bearings are made in sintering and hipping processes. These bearings can function properly in hydrodynamic (thick-film) or thin-film lubricating conditions [24].
5. **Cadmium:** a very good choice for elevated temperatures. However, high cost and toxicity of cadmium have restricted its application in bearing industry [2].
6. **Sliver:** provides excellent compatibility properties (anti-scoring and anti-seizing) for bearings. Silver is normally electroplated onto a steel backing due to its high cost.

2.2.3 Lead-containing sliding bearings

Lead (Pb) and its alloys are widely used as a sliding bearing material due to the significant benefits that it can provide for the bearing industry. Compared with tin-based whitemetal, lead-based whitemetal is now being much more widely used because of its lower cost and almost equivalent bearing properties. It is also well known that lead is more effective than tin as a soft phase alloying addition, which confers the necessary anti-scoring and anti-friction properties with low wear.

Lead-containing aluminum alloys, copper-lead alloy and lead bronze (tin combines with copper to form bronze) are found in many applications, typically in the automobile industry. In these alloys lead remains in a free state dispersed in the

aluminum, copper, or bronze matrix. This free lead provides the bearing properties, while the aluminum-based and copper-based matrices supply the strength. It was proved by Fujita [19] that the role of lead is mostly that of a boundary lubricant layer at the surface of the asperities. A low modulus of elasticity is required in a metallic bearing alloy to ensure good conformability with the journal surface. Apart from indium, lead has the lowest modulus of elasticity of all the soft phases alloying with aluminum, copper and bronze. Also, one advantage of lead addition to bronze is the increased plasticity afforded by the lead constituent, which can compensate to some extent for want of fit or alignment of bearings [27].

2.2.3.1 Types

Sliding bearings, which have lead in their compositions, can be sorted in five major categories:

1. **Nonmetallic lead-containing compounds:** Lead is used as filler in many kinds of nonmetallic bearings. For example, in PTFE based bearings, lead is exploited to provide bearings with the necessary criteria such as better functionality.
2. **Lead-base babbitts:** SAE 13, SAE14, and SAE 15 are three important types of these babbitts. Having the best combination of the required criteria for a sliding bearing amongst all lead-containing bearings, lead-base babbitts are mostly famous for their outstanding compatibility, embeddability, and conformability under limited lubricating conditions [2].

3. **Leaded bronze:** It has excellent anti-scoring characteristic but poor physical properties, limited load capacity and narrow operating temperature [2].
4. **Tin bronze:** It contains a lead content much less than that of the leaded bronze. Tin bronze has improved load capacity compared with leaded bronze. However, a proper lubrication is needed in tin bronze bearings [2].
5. **Copper-lead:** Bearings made with copper-lead materials have good wear resistivity and better load capacity than soft babbitts. However, steel backing is normally required in these types of bearings [24].

2.2.3.2 Characteristics

The characteristics of lead-containing bearings for operation against a steel counterface, and under very good conditions of lubricant film integrity, counterface finish, mechanical alignment, and temperature control are presented in Table 2.1. These properties include:

1. **Good compatibility:** The wettability of lead with all ordinary oils at normal running temperatures of sliding bearings is good. Therefore, lead-containing bearings tend to remain oily during their operation that improves anti-weld and anti-scoring properties of the bearings in lubrication starvation situations. This property is good in lead-base babbitts and copper-lead bearings; however, it is poor in tin-babbitts [1, 22].
2. **Average conformability:** Lead is considered as a soft material; thus, it can be scraped to adjust for slight misalignment or it can be relined when worn or

damaged. Most types of lead containing bearings show average conformability property, while this property is good in lead babbitts [1, 2].

3. **Satisfactory embeddability:** The ability of absorbing foreign particles of lead is better than any other existing lining metals, especially in the near metal-to-metal contact situations at starting motion; for instance, undesirable foreign matters can be easily embed into the lead-containing bearing surface. However, the embeddability of lead is much poorer than that of the most types of polymer-based bearings. Therefore, except for lead-based babbitts, the embeddability of lead-containing bearings is considered to be at the average level [1, 22, 24].
4. **Acceptable load capacity:** Mostly with backing layers, lead-containing bearings have acceptable load bearing capacities. Such capacity can be normally improved by using an intermediate layer or increasing the thickness of the surface layer in a sliding bearing [1].
5. **Excellent functionality:** In sliding bearings, lead exists as a soft phase alloying element that confers anti-scoring, anti-friction, and anti-wear properties to the bearings. When properly applied as a lining material, lead has an excellent adhesion to steel, cast iron, and bronze; thus, improved wear resistance can be obtained in these materials [22].
6. **Poor fatigue resistance:** Lead-base sliding bearings cannot properly withstand in cyclic loads; therefore, the fatigue resistance of different types of lead-based sliding bearings is considered either medium or poor [1].

7. **Average corrosion resistance:** As a corrosion resistant metal, lead is not highly corroded by the acid introduced into the lubricants of engines by the combustion of sulfur containing fuels. The corrosion resistance of lead-containing slider bearings is considered as medium [1, 2].
8. **Cost-effective:** Tin-based white metal has always been regarded as superior to lead-based materials. However, the price of tin has soared so drastically that lead-based white metal is now being much more widely used because of its lower cost and almost equivalent bearing properties [22].

Table 2.1 Lead-containing bearings characteristics ⁽¹⁾ [1]

Steel	Lead Babbitt (0.25-0.5) (mm)	A	A	A	F	B	14
Medium-Lead Bronze	Lead Babbitt (0.25-0.5) (mm)	A	A	A	F	C	14
—	Tin Bronze-High Lead	D	D	D	D	E	21
—	Tin Bronze-Medium Lead	E	E	E	C	D	28
Steel	Copper-Lead	A	B	B	E	C	21

Notes:

(1) Rated on scale A through F, where A is excellent and F is poor

(2) Corrosion by fatty acids that can form in petroleum-base oils

(3) Approximates maximum safe unit loading

2.2.3.3 Development of lead-free bearing materials

Although lead imparts several good characteristics to the bearings, it is considered the most ubiquitous toxic metal. The inherent toxicity of lead causes deleterious, acute and chronic effects on plants and animals, and cumulative toxic effects on humans. In terms of human health, lead can cause neurologic effects such as peripheral or chronic neuropathy, hematologic effects such as anemia, renal effects or even carcinogenesis effects [3].

When lead-containing bearings are used, lead exists in the atmosphere in solid, particulate, dust or vapor forms. About 90% of lead particles in ambient air are so small that will remain in the lungs. Although the lead absorption rate into the body is slow, but lead excretion rate is much slower [3]. Therefore, environmental regulations around the world have been targeted to eliminate the usage of lead-containing bearing materials. There is a strong demand from the bearing manufacturers such as Canadian Babbitt Bearings Ltd. and bearing users such as Pratt & Whitney Canada to replace lead-containing bearing materials by equivalent, comparable or superior new lead-free bearing materials. Thus, the new developed bearings will become the next generation of bearing materials.

2.3 PTFE Materials

2.3.1 General

Polytetrafluoroethylene (PTFE) is an engineering plastic more commonly known as Teflon®, which is a DuPont company registered trademark. In April 6, 1938, Dr. Roy

J. Plunkett was working with his colleagues on Freon® refrigerants at DuPont's Jackson Laboratory in New Jersey. He realized that his compressed tetrafluoroethylene sample had accidentally polymerized. The result was a white, waxy solid, which was called PTFE [28]. PTFE was patented in 1941 and Teflon® trademark was registered by DuPont in 1945. The first products were sold commercially in 1946 and the development of the new products of PTFE and their applications soared drastically that by 1950 over a million pounds (450 t) was annually produced by DuPont [28].

A versatile thermoplastic fluoropolymer resin with unique chemical, thermal, tribological, and electrical properties; PTFE is composed of long, straight chains of fluorinated carbons, as shown in Figure 2.4. The unique properties of polytetrafluoroethylene are due to the backbone of carbon atoms symmetrically surrounded by fluorine atoms [29].

Figure 2.4 Polytetrafluoroethylene monomer ($n = 10000-100000$) [22]

Some of the major suppliers of PTFE include DuPont INC., ICI Americas INC., Asahi/America Fluoropolymers, Asahi/America Glass, AGC Chemicals Americas Compounds, Ausimont, Hoechst Fibers Industries, Montedison USA INC., and DaikinKogyo [22].

2.3.2 Types of PTFE materials

PTFE is available in three different forms. Each form can give the end product some particular traits and is more suitable for a specific manufacturing technique. These forms are [29]:

1. **Granular resins:** white granular powder used in compression molding or ram extrusion manufacturing techniques. In compression molding technique, PTFE granular resins are normally processed by compression at room temperature followed by sintering. These materials are non-adhesive and have good toughness at lower temperatures. The maximum service temperature of these resins is 260°C. PTFE granular resins are used to fabricate mechanical seals and bearings, gaskets, insulators for high frequency and high temperature cables, and non-adhesive surfaces.
2. **Fine powders:** white smooth powders, which are specifically prepared for processing with the paste-extrusion technique to fabricate thin sections. These types of powders can offer the same properties as granular resins. Electrical insulations, extruded hose, and pipe linings are among the products that can be fabricated using PTFE fine powders.

- 3. Aqueous dispersion:** a milky water-base emulsion of PTFE and a wetting agent. The application of PTFE aqueous dispersion includes the metal coating or porous structure impregnating. The properties of PTFE aqueous dispersion is identical to those obtained with granular resins, while having the ease of use advantage as a liquid form material. Some application of PTFE aqueous dispersion are coating fabrics for electrical insulation and impregnating braids for gaskets.

2.3.3 Fabrication of PTFE materials

Manufacturers mostly use three different methods to produce PTFE materials. These methods are [30]:

- 1. Suspension polymerization:** In this method the end product is either granular or fine powder of PTFE. To become polymerized, liquid form of tetrafluoroethylene monomer (TFE) is pumped into a vigorously shaken reaction chamber. The chamber is under pressure and is filled with purified water and a free-radical catalyst as the initiator.
- 2. Dispersion polymerization:** An aqueous dispersion form of PTFE is synthesized by polymerization of TFE in a gently agitated reaction chamber in the presence of purified water and a reaction agent.
- 3. Direct fluorination:** In this process PTFE is made through the direct replacement of hydrogen atoms on polyethylene with fluorine at 20°C.

2.3.4 Characteristics

PTFE is a polymer with remarkable properties. Mechanical, thermal, chemical, and electrical properties of Teflon® are presented in Table 2.2 to Table 2.5. The unique or outstanding properties of PTFE are listed as follow [4-7]:

- Extremely slippery surface with the lowest coefficient of friction among all solid materials on the earth
- Good stress-crack resistance
- High compressibility
- Exceptional non-stick properties
- Outstanding thermal stability
- Excellent thermal insulation
- Good chemical stability
- Outstanding corrosion resistivity
- Spectacular nuclear radiation, ultra violet rays, ozone, and weather resistivity
- Remarkable non-contaminating properties
- Good moisture resistance
- Notable non-flammability
- Good dielectric strength and low dissipation factor

Table 2.2 Mechanical properties of Teflon (Courtesy of DuPont)

Specific Gravity	D792	—	2.15
Tensile Strength	D1457 D1708 D638	MPa (psi)	21-34 (3,000-5,000)
Elongation	D1457 D1708 D638	%	300-500
Flexural Modulus	D790	MPa (psi)	496 (72,000)
Folding Endurance	D2176	(MIT) cycles	$>10^6$
Impact Strength	D256	J/m (ft·lb/in)	189 (3.5)
Hardness	D2240	Shore D pencil	50-65
Coefficient of Friction, Dynamic	D1894	—	0.05-0.10

Table 2.3 Thermal properties of Teflon (Courtesy of DuPont)

Melting Point	D3418	°C (°F)	327 (621)
Cure Temperature	—	°C (°F)	379-429 (715-805)
Flame Rating	UL94	—	V0
Limiting Oxygen Index	D2863	%	>95
Heat of Combustion	D240	MJ/kg (Btu/lb)	5.1 (2,200)

Table 2.4 Chemical properties of Teflon (Courtesy of DuPont)

Chemical/Solvent Resistance	D543	—	Excellent
Water Absorption, 24 h	D570	%	<0.01
Salt Spray Resistance ⁽¹⁾ -on aluminum -on steel	B-117	Hours Hours	744+ 192
Detergent Resistance ⁽²⁾ -on aluminum -on grit-blasted aluminum -on grit-blasted steel	—	Hours Hours Hours	264 624 24
Weather Resistance	Florida Exposure	Years Unaffected	20

Table 2.5 Electrical properties of Teflon (Courtesy of DuPont)

Dielectric Constant	D150	1 MHz	2.1
Dielectric Strength ⁽³⁾	D149	V/μm	18
Dissipation Factor	D150	1 MHz	<0.0001
Arc Resistance	D495	sec	>300
Volume Resistivity	D257	ohm.cm	>10 ¹⁸
Surface Resistivity	D257	ohm/sq	>10 ¹⁸

Notes:

(1) Salt Spray Resistance: 5% NaCl at 35°C/95°F, hours to failure

(2) Detergent Resistance: hours to failure

(3) Dielectric Strength: 100 micrometers film

2.3.5 Applications

Because of its unique chemical, electrical, thermal, mechanical and tribological properties, PTFE is widely used in several industries. These industries include [29]:

1. **Aerospace:** Excellent anti-frictional property and chemical stability make PTFE a very good choice for sealing applications in turbine engines and rotary actuators. Also, since polytetrafluoroethylene is a lightweight material with good stress-crack resistance, it is ideal for hose and tubing for hydraulic, pneumatic, fuel, and oil systems.
2. **Automotive:** PTFE is utilized for several purposes in automotive industry. Sliding bearings, hydraulic clutch piston rings, shaft and compressor seals, and head gasket coatings are some of the applications. Also, due to the high-temperature and high-chemical resistance of PTFE, it is used for auto fuel lines.
3. **Semiconductor manufacturing:** Polytetrafluoroethylene is used to make semiconductor chips. For point-of-use filters, PTFE membrane elements are useful in filter cartridges. In addition, in wafer carriers, wet-bench equipments, and processing cassettes, PTFE is also used.
4. **Electronic/Electrical:** PTFE has a high dielectric strength and a low dissipation factor. Thus, it is a useful choice in electrical applications, such as code-approved plenum cable and fire alarm equipment cables. Also, in electronic applications PTFE is used to make printed circuit board laminates, since it can be used to fabricate very thin substrates.

5. **Petrochemicals:** Due to the high corrosion resistance, PTFE is used for lining pipes, tanks, fittings, valves and pumps in petrochemical industry. Also, PTFE provides higher flow rates than metallic piping because of the low friction coefficient of polytetrafluoroethylene.
6. **Medical:** Materials used to produce medical parts such as synthetic human body parts must meet some stringent requirements. PTFE is considered as an aseptic material because of its non-contaminating properties and chemical stability. Therefore, polytetrafluoroethylene is used to make cardiovascular patches, vascular grafts, ligaments, soft tissue patches, and surgical membranes.
7. **Other applications:** PTFE is used in many other applications. Some of these include industrial coatings, optical radiometry, ground water sampling, breathable waterproof fabrics, and non-stick cookware.

2.4 PTFE Bearings

2.4.1 Features

PTFE is considered as a superior sliding bearing material, because it can meet the required criteria for sliding bearing materials. High temperature capability, outstanding thermal stability, and extremely low coefficient of friction, especially at higher specific loads and lower speeds, make PTFE an attractive polymer for sliding bearings. Also, as a self-lubricating polymer, it has the capacity to run under conditions where full film lubrication cannot be achieved, dirty conditions prevail, or the use of liquid lubricants is

undesirable or impossible. Consequently, a wide range of operating temperatures (–250 to +240°C) can be achieved with the high temperature stability of Teflon® and in the absence of lubrication. Furthermore, since PTFE is a solid lubricant, the design and manufacturing steps for grease nipples or oilways would be eliminated by which a low-cost bearing can be produced [8, 31].

PTFE is a good self-lubricating material. When slides against a smooth and clean substrate, PTFE forms a thin and highly oriented transferred film of itself on the substrate. This film provides the excellent anti-friction property of PTFE bearings. Unfortunately, unfilled state of PTFE has a low wear resistance and consequently has a limited value as a bearing material. However, this behavior can be drastically improved in PTFE composites by incorporation of fillers, whilst the low friction coefficient of PTFE is considerably maintained [9, 32].

2.4.2 Frictional characteristics

PTFE is well known for its low friction coefficient among polymeric materials. This characteristic results from the smooth molecular profile and low intermolecular cohesion of PTFE. Polytetrafluoroethylene has no unsaturated bonds and it is not easily polarized. During sliding contact against a smooth clean substrate, extended chain-linear molecules of PTFE, $-(CF_2-CH_2)_n-$, forms a thin transfer film upon the bearing surface and its mating counter-faces. This transferred film, which is generally found thinner and more highly oriented than that of other transferring polymers, provides the unusually low coefficient of friction of PTFE [7, 9, 33].

The deformation of PTFE materials under load is considered as viscoelastic. Therefore, the coefficient of friction variation with the load follows the equation $\mu = \beta F^{-0.1}$, where μ is the friction coefficient, F is the applied load, and β is a constant. This equation shows that the coefficient of friction of PTFE materials decreases by increasing the load. However, it was proved that beyond the load limit of PTFE, the friction increases sharply [28].

It was proved by Zhang *et al.* [6] that high sliding speed, very low bulk temperature, and a rough counterface, more than 1 μm , may reduce the antifriction property of PTFE. These factors interfere with the formation of transfer films, or with the easy drawing of molecular chains out of the material.

2.4.3 Tribological behavior of unfilled PTFE bearings

PTFE gets its desirable antifriction properties from the low-shear-strength thin film that is generated on the surface of counterfaces during sliding. However, the transferred film can be easily removed when sliding continues, since the adhesion of this transferred film to the counterface is relatively poor. The high rate, cyclic film formation and destruction process cause PTFE exhibit cold-flow phenomenon under load and high wear rate at normal friction conditions [4, 9, 33].

Furthermore, the tribological behaviour of a polymer composite can be associated to its temperature related properties. When two materials sliding against each other, heat will be generated at asperities and temperature would be increased at the interfaces. Therefore, the adhesive wear resistance of a polymer-based sliding bearing depends on its

thermal stability, its heat dissipation rate or thermal conductivity, and its ability to maintain a good integrity at the resultant temperature. Thus, unfilled PTFE generally exhibits a high wear rate due to its low thermal conductivity, while PTFE reinforced by hard particulate or fibrous fillers exhibits better tribological properties [4, 7].

2.5 PTFE Composites

2.5.1 Significance

Despite its excellent properties, virgin PTFE is inadequate for a number of demanding engineering applications. In particular, due to the high cold flow or creep rate of PTFE, it has poor mechanical properties that keep it out of mechanical applications. In addition, high adhesive wear rate, excessive viscoelastic deformation under load, and low abrasion resistance of PTFE limit its application in practice [4, 5, 7].

A variety of materials, as fillers, have been mixed with PTFE to improve its properties and make tailor-made compounds for many end-uses. These fillers, which must withstand the sintering temperature of PTFE, may be any organic or inorganic compounds, different metal oxides, fibers, elements, alloys, ceramics, and polymers. The main fillers with varying degrees of success in PTFE composites are graphite, glass fibers, bronze, polyimide, PPDT fibers, carbon fibers, Aramid fibers, CaF_2 , MoS_2 , Al_2O_3 , CeO_2 , CeF_3 , La_2O_3 , Cu_2O , CuS , ZnO , Pb , PbS , Pb_3O_4 , and PbO .

In addition to the chemical composition of fillers, many other factors including their state and size can greatly affect the properties of the filled compounds. For instance,

it was proved by Speerschneider *et al.* [8] that filler's geometrical shape has an effect on the coefficient of friction and wear resistance of PTFE composites. In addition, the effect of filler's aspect ratio on the tribological properties of PTFE was somehow investigated by Briscoe *et al.* [9]. Therefore, considering the end application of the PTFE composite, the filler selection should be carefully done to have the best balance of properties. Unfortunately, no general theory is available to predict the behaviour of fillers from first principles; therefore, the proper selection of fillers is somehow empirically [32].

2.5.2 Existing PTFE composites properties

Although PTFE composites were extensively studied in the past, much of the obtained results are either poor or non-reproducible. This is due to the fact that the pedigree of the constituents and the fabrication information of the composites remain vague. In addition, due to the lack of a standard for PTFE materials, the results of the tests that performed to characterize the developed composites are not comparable. For instance:

- Since the results obtained by Zhao *et al.* [6] from the wear test are presented in weight loss; they are only useful for the comparison purposes at their specific case and are not comparable to any other research works.
- The lowest friction coefficient reported by Li *et al.* [5] is about 0.21 for a composite of PTFE filled with 30 (vol.%) of nanometer ZnO where the tests were conducted at room temperature, under a load of 200 N, with a speed of 0.431m/s, for 5 to 120 min, and against a stainless steel counterface. However, the results of

the wear tests presented in wear volume loss are not comparable to any other test results obtained by other researchers.

- The lowest coefficient of friction obtained by Tanaka *et al.* [10] is about 0.2 for a mixture of PTFE with 40 wt.% bronze under the wear tests conducted in room temperature, under a load of 10 N, with a speed of 0.1 m/s. However, no information is available about the test duration and the material of the mating surface.

Owing to the establishment of some new standards for PTFE materials [13, 14], the data presented by the researchers in recent years become more reliable. The results obtained by Khedkar *et al.* [7] for a composite of 75%PTFE+18%CF+7%graphite (vol.%), with a hardness value of 66 shore D, show a coefficient of friction of 0.17, and the specific wear rates of 9 and 4 ($\text{mm}^3/\text{N.m}$) $\times 10^{-5}$ for 1 km and 5 km tests respectively. The tests were conducted in the laboratory environment, against a steel ball, under a load of 5 N, with a sliding velocity of 0.1 m/s. Regarding mechanical properties, it was reported that the best ultimate tensile strength at 23 °C was 19 MPa of PTFE filled with 25 wt.% of glass fiber. Other reported mechanical properties for this composite include the yield strength of 10 MPa, the Young's modulus of 800 MPa, an elongation up to 240%, and a hardness of 65 shore D [28].

2.5.3 Effects of fillers on the tribological properties

The desirable combination of low wear rate and low friction cannot be achieved by virgin PTFE. Although the coefficient of friction of pure polytetrafluoroethylene is very low, its wear rate is extremely high. Through by incorporation of a variety of fillers, the wear resistance of PTFE can be markedly improved without sacrificing the low friction characteristic [34].

Except for the extreme coarse particles, coefficient of friction is more dependent on the quantity of the filler than on the filler type. In most cases, μ remains very close to the coefficient of friction of pure PTFE [34, 35]. The mechanism of fillers in reducing wear has been largely focused by many researchers. No clear and proven theory is available to describe the wear reduction role of fillers in PTFE. However, there appear to be three main explanations or hypotheses about the wear-reducing mechanism of fillers:

1. **Transfer film adhesion:** One explanation suggests that fillers provide effective adhesion between the transfer film and the counterface. Certain oxides are good examples of this mean. The nature of the enhanced film adhesion mechanism is either chemical or physical. The chemical interactions, which are promoted by the high temperature generated at the sliding interface, can increase the transfer film adhesion [34]. For instance, the catalytic effect of copper was proved by Pocock *et al.* [36]. In contrast, there is no evidence of enhanced chemical reactivity of PTFE with carbon and glass fibres while these fibres are very effectual in wear reduction [35].

2. **Load support:** Another hypothesis is that the wear-reducing role of PTFE composites stems from the preferentially supporting the applied load by fillers. In this case, the contact sliding surface within which frictional tractions are applied directly to the PTFE matrix is limited. Hard inorganic fillers can be inserted in this group, since excess filler concentration can be observed on the composite surface after prolonged sliding [33, 34].
3. **Retarding subsurface crack propagation:** In the last suggested hypothesis it is stated by Bahadur *et al.* [34] that fillers can lower the wear rate of PTFE by interrupting crack propagation and reducing subsurface deformation. Thus, the fillers prevent the production of large worn sheets by governing the shape and size of wear fragments. As a result, the nature of the transfer film can be determined by the type of debris produced during the sliding contact [7, 33]. In case of filled PTFE composites, the worn materials have particle forms. These very small particles can be easily locked into the counterface surface crevices, resulting in a coherent transfer film on the asperities. In contrast, worn materials of unfilled PTFE have fragmented sheet forms. These thicker materials are locked between the discrete locations of asperities and can be easily removed by scraping action during the sliding process [34].
4. **Other possible factors:** The causes of enhanced wear resistance of filled PTFE are somehow obscure and may be a combination of several factors. Lower wear rate of PTFE composites can be due to their improved mechanical properties. Also, many types of fillers such as carbon fibres can

improve the thermal conductivity of the composites. This might be another key factor to reduce wear.

2.5.4 Fabrication

PTFE has a melting point of 327°C. At temperatures above the melting point, PTFE never becomes fluid but it becomes a self-supporting gel. Even at 380°C, the viscosity of Teflon® is about 10 GPa.s and the resin would not flow. Therefore, it cannot be processed by the traditional melt-processing techniques [32, 33]. Depending on the type of PTFE materials, different methods are used to fabricate the composites [28, 29]:

1. **PTFE Granular Powders:** This fabrication method involves the compression of the powder to prepare a preform, sintering the preform, followed by machining to make the final parts. In order to compress the powder, one of the following molding techniques is used:
 - Compression molding for basic stock shapes such as sheets or billets
 - Isostatic molding to make complicated shapes such as thin wall parts
 - Automatic molding to make repetitive simple shapes
 - Ram extrusion to make solid rods and tubes
2. **PTFE fine powders:** Paste extrusion method is mostly used for this type of powders. Prior to extrusion, fluoropolymer resin is mixed with a hydrocarbon liquid to facilitate extrusion. To remove this liquid, composite is heated after extrusion.

- 3. PTFE aqueous dispersions:** This fabrication method involves immersing a part in dispersion either to coat the part or to impregnate its porous structure. The part is then heated to remove the water and to coalesce the resin particles.

2.6 Tribaloy Alloys

2.6.1 Superalloys

Superalloys are alloys based on group VIIIA elements of the periodic table. These alloys are generally developed for elevated-temperature applications where superior mechanical strength, high surface stability, good creep resistance, and excellent corrosion resistance are frequently required. Typical applications of superalloys are aerospace industry, nuclear reactors, chemical plants, and power plants. Three major classes of superalloys include cobalt-base superalloys, nickel-base superalloys, and iron-base superalloys [37, 38]. Generally, superalloys can be classified into three groups [39]:

(1) carbide-strengthened alloys; (2) intermetallic Laves phase alloys; and (3) solid solution-strengthened alloys.

2.6.2 Stellite alloys

Invented by Elwood Haynes in 1907, Stellite alloys are carbide-strengthened alloys, a range of cobalt-base superalloys. Stellite alloys properties include high wear resistance, excellent corrosion resistivity, and astounding hardness and toughness. These alloys mostly contain about 50-60 wt% Co, 20-30 wt% Cr, 5-20 wt% W, and 0.1-1 wt% C. Considering the final application of the alloys, some other elements such as nickel, molybdenum, iron, tantalum, and niobium with different weight percentages can be also

added. Typical applications of Stellite alloys are cutting tools, jet engine turbine blades, poppet valves, and high corrosion resistant machine parts [38, 40].

Stellite alloys are generally strengthened by the precipitation of carbides in a cobalt matrix; the typical microstructure is shown in Figure 2.5.

Figure 2.5 Microstructure of Stellite 21 [41]

Considering the volume content of carbides, there are two major groups of Stellite alloys: high carbon alloys and low carbon alloys. Normally, the wear resistance increases

with the higher volume fraction of carbides, while the corrosion resistance tends to rise by increasing the chromium content. Therefore, high carbon Stellite alloys have superior wear resistance, while low carbon Stellite alloys have better ductility and corrosion resistivity [40].

2.6.3 Tribaloy alloys

Tribaloy alloys, which came to the market around 1980, are among the cobalt-base or nickel-base classes of superalloys. The composition of cobalt-base Tribaloy alloys varies according to their application; however, the main alloying elements are Co, Mo, Cr and Si. Due to the allotropic nature of cobalt, both face centered cubic (FCC) and hexagonal close packed (HCP) crystal structures can be present in these alloys. However, some thermal treatments and higher chromium content will increase the probability of the high temperature FCC cobalt transforming to HCP at room temperature. Tribaloy alloys stand out for their excellent corrosion and wear-resistance. The former is because of the presence of chromium while the latter is due to the existence of molybdenum and silicon in the composition of Tribaloy alloys [11, 42].

Tribaloy alloys, which are normally hypereutectic, are intermetallic materials containing a large volume fraction (30 - 70 vol.%) of a hard, intermetallic Laves phase in a much softer matrix, as shown in Figure 2.6. It is the presence of this large volume fraction of Laves phase that enables these materials to achieve their good wear resistance. The intermetallic ternary Laves phase in cobalt-based Tribaloy alloys is $\text{Co}_3\text{Mo}_2\text{Si}$ or CoMoSi . The Laves phase in Tribaloy alloys is much softer than carbides in Stellite

alloys; however, it is hard enough to resist wear in boundary or lack of lubrication conditions [40, 42]. Tribaloy alloy family consists of a series of alloy categories, designated as T-400, T-700, T-800 and T-900. Among them, T-400 and T-800 are the most popular ones. Because the Laves phase is so abundant in these alloys, its presence governs all the material properties. Accordingly, the effect of the matrix composition in these alloys is less pronounced than in the case for Stellite alloys.

Figure 2.6 Microstructure of Tribaloy T-400 [40]

The major difference between Stellite alloys and Tribaloy alloys is that the former gains wear resistance from carbides and the latter from Laves phase. The hardness of the carbides is in the range above Vickers 2000 (HV) and that of the Laves phase is between 1000 ~ 1300 (HV). The Laves phase is hard enough to resist wear, while it is not so hard to become a cutting tool to wear away a mating surface.

2.6.4 Newly developed Tribaloy alloy T-401

As a result of the hard brittle nature of the Laves phase, Tribaloy alloys possess a relatively low resistance to crack propagation and little capacity for plastic flow [43, 44]. Although wear resistance is a necessity for Tribaloy alloys, other properties such as ductility, fracture toughness and high-temperature oxidation resistance are also important for some specific applications.

To improve these properties, a new Tribaloy alloy, designated as T-401, has been developed at Deloro Stellite Inc. The chemical composition of T-401 accompanied with the chemical composition of some other Tribaloy alloys are presented in Table 2.6 for comparison.

Table 2.6 Chemical composition of Tribaloy alloys [11]

T-	401	Bal.	17	22	1.2
T-	400	Bal.	8.5	28.5	2.6
T-	800	Bal.	17	28	3

Compared with the conventional Tribaloy alloys such as T-400, silicon, and molybdenum contents are largely reduced, while chromium content is increased. Due to the lower contents of Si and Mo, which are the key elements for Laves phase formation, the solidification process is changed from hypereutectic to hypoeutectic, that is, the primary phase of T-401 is not Laves phase, but dendritic cobalt solid solution, as shown in Figure 2.7. As a result, T-401 has a better ductility compared with traditional Tribaloy alloys. Previous research reported that the tensile strength of T-401 is 678 MPa, which is very close to the tensile strength of conventional T-400 (690 MPa) [11, 40, 42].

However, as for the most materials, increasing ductility is usually accompanied with decreasing hardness and wear resistance, it was reported that T-401 has lower hardness and wear resistance than T-400, but it is still wear-resistant. Immersion corrosion tests also demonstrated that T-401 has corrosion resistance superior to T-400 in H_2SO_4 , HNO_3 and HCl acids [45].

Due to the superior properties described above, it is expected that the application of newly developed T-401 as filler in PTFE bearings, would provide us with a new type of sliding bearings with superior mechanical properties and wear/corrosion resistance to those of currently used sliding bearing materials.

Figure 2.7 Microstructure of Tribaloy T-401 [40]

Chapter 3: Specimen Fabrication

3.1 Raw Materials

3.1.1 Constituents

The matrix material for the developed PTFE composites is PTFE powder. In order to select the reinforcements properly, a wide range of possible fillers and additives was studied. Although it is impossible to theoretically predict the behavior of fillers in a PTFE matrix, the effort was to select the fillers with more chances of success. Therefore, the method adopted to solve the problem was empirical and evolutionary, while guided by previous experience in the design of dry bearings. Finally, it was planned to mix the PTFE matrix with four different types of fillers to obtain some specific properties in the final composites and compare the properties between the fillers. The selected materials include:

1. **Tribaloy alloy T-401:** It was added to PTFE matrix to improve its adhesive wear resistance. Also, as introduced in the Chapter 2, T-401 has lower hardness than traditional Tribaloy alloys such as T-400. Therefore, compared with the conventional Tribaloy alloys, the possible pulled-out particles of T-401 during bearing operation can be less abrasive to the bearing counterface. In addition, since PTFE matrix is much softer than metals, if traditional Tribaloy alloys are used as the reinforcement, the large difference

of hardness and mechanical properties between the matrix and the reinforcement would result in a weak interface between the two phases. However, different from traditional Triballoy alloys, T-401 has improved ductility due to the primary solid solution, which provides this alloy with better accommodation to the matrix deformation. Furthermore, T-401 has excellent corrosion resistance, which meets the requirement of sliding bearing service environments.

2. **Bronze:** It is widely used in bearing industry as a matrix material because of its versatile mechanical, tribological, and chemical properties. Bronze, which is a copper-base alloy, was selected as one of the fillers in the developed PTFE composites due to its high thermal conductivity. It is believed that the wear resistance of PTFE materials can be greatly enhanced due to the better heat dissipation properties of bronze in the PTFE composites. The anticorrosive and antifriction properties of bronze are also very good; however, these properties are not as good as those of PTFE. Also, the bronze filled PTFE materials can be easily machined that keeps the overall cost of the bearings very low.
3. **Carbon and graphite:** They are interchangeably used; however, carbon is a substance with 93-95% pure carbon, while graphite contains 99% pure carbon. Both carbon and graphite consist of carbon atoms arranged in hexagonal arrays. Two major types of carbon fibers include PAN-based fibers and Pitch-based fibers both of which have good chemical resistance to corrosive environments. PAN-based fibers, which are more commonly used, offer the

highest strength and low to high modulus. Pitch-based fibers have high to ultra-high modulus and low strength. It is believed that the presence of hard PAN-based carbon fibers, which are embedded in the PTFE matrix, can increase the load capacity of the bearings. Other mechanical properties such as creep resistance, compressive strength and bending strength may also be improved by use of carbon fibers in the developed composites. Regarding tribological properties, it is expected that PTFE composites filled with carbon fibers would possess better wear resistance due to the improved heat dissipation and load supporting capabilities. Graphite was also employed since it is an excellent solid lubricant and can improve the heat conductivity of the PTFE composites as well.

3.1.2 Teflon® 7C

Teflon® 7C, which is a fluoropolymer granular resin of DuPont, was selected as the PTFE matrix of the composites. This resin is a white powder with irregular, fibrous particles that capture fillers very well. With the fluoropolymer small median particle size of 28 μm , composites with less porosity can be achieved. Filled compounds of PTFE 7C are used in many applications such as piston rings and gaskets. Teflon® 7C is not considered to contain toxic chemicals according to its material safety data sheet (MSDS). General and mechanical properties of Teflon® 7C are presented in Table 3.1.

Table 3.1 General and mechanical properties of PTFE 7C (Courtesy of DuPont)

Average Bulk Density	g/cc (lb/in ³)	0.25 (0.009)
Average Mold Shrinkage (at preform pressure of 35 MPa [5,000 psi])	%	6
Average Particle Size	μm	28
Standard Specific Gravity	—	2.16
Initial Melting, Peak Temperature	°C (°F)	342 ±10 (648 ±18)
Second Melting, Peak Temperature	°C (°F)	327 ±10 (621 ±18)
Tensile Strength	MPa (psi)	21-34 (3,000-5,000)
Elongation at Break	%	400

3.1.3 Ecka bronze powder

Spherical bronze powder, 89/11 AK, with a median particle size of 45 μm, was obtained from Ecka Granules Company. The applications of the spherical bronze powder include sintered bearings, diamond tools, fillers for plastics, and friction lining. No specific safety precaution is given in the MSDS of this material. The general properties of this material are presented in Table 3.2.

Table 3.2 The properties of bronze particles (Courtesy of Ecka Granules)

Average Bulk Density	g/cc (lb/in ³)	8.45 (0.30)
Average Particle Size	μm	45
Tin (Sn) Content	%	10.6
Phosphorous (P) Content	%	0.35
Hardness	HRC	15
Thermal Conductivity	W/m.k	63 ⁽¹⁾

Note:

(1) At 20°C

3.1.4 PANEX carbon fibers and graphite

Four different types of chopped PAN-based carbon fibers and a milled PAN-based graphite powder were obtained from Zoltek Company. The mechanical properties and diameters of all the fibers are the same, but they are different in length.

The designations, length, and diameter of the fibers and the graphite powder are:

- PANEX® 33 CF chopped carbon fibers, 1.0 inch length, 7.2 μm diameter
- PANEX® 35 CF chopped carbon fibers, 1/2 inch length, 7.2 μm diameter
- PANEX® 35 CF chopped carbon fibers, 1/3 inch length, 7.2 μm diameter
- PANEX® 35 CF chopped carbon fibers, 1/8 inch length, 7.2 μm diameter
- PANEX® 30 MF high purity milled graphite, 150 μm length, 7.4 μm diameter

These materials are normally used for plastic compounding applications requiring high strength, high modulus and good tribological properties. Toxicological information of these materials does not show any known health hazard. The properties of the short fibers and graphite are presented in Table 3.3 and Table 3.4 respectively.

Table 3.3 Properties of carbon fibers (Courtesy of Zoltek Company)

Tensile Strength	MPa (ksi)	3800 (550)
Tensile Modulus	GPa (Msi)	228 (33)
Electrical Resistivity	ohm-cm (ohm-in)	0.00172 (0.0007)
Density	g/cc (lb/in ³)	1.81 (0.065)
Carbon Content	%	95

Table 3.4 Properties of milled graphite (Courtesy of Zoltek Company)

Tensile Strength	MPa (ksi)	3600 (500)
Tensile Modulus	Gpa (Msi)	207 (30)
Electrical Resistivity	ohm-cm (ohm-in)	0.0014 (0.0006)
Density	g/cc (lb/in ³)	1.75 (0.063)
Carbon Content	%	99.5
Thermal Conductivity	W/m.k	85 ⁽¹⁾

Note:

(1) At 20°C

To investigate the effect of the filler aspect ratio on the final properties of the composites, all of these materials were initially mixed with PTFE resin. However, the experimental results showed that the 1, 1/2 and 1/3 inch length carbon fibers were not suitable since visible cracks were found in the composites, as indicated in Figure 3.1. These cracks may be due to the high viscosity of PTFE, since resin could not be infused into the long carbon fibers, which were provided in a bundle form.

Figure 3.1 Visible cracks in the composites filled with longer carbon fibers

3.1.5 T-401 Tribaloy alloy powder

The T-401 powder was supplied by Deloro Stellite Inc. The median size of the powder is 40 μm . The general properties of T-401 alloy are presented in Table 3.5.

Table 3.5 The properties of T-401 particles [3, 40]

Tensile Strength	MPa (ksi)	678 (98)
Corrosion Rate	mils/yr	380 ⁽¹⁾ 40 ⁽²⁾ 2.8 ⁽³⁾
Endurance Limit	MPa	400
Average Bulk Density	g/cc (lb/in ³)	8.63 (0.312)
Hardness	HRC	49
Thermal Conductivity	W/m.k	10 ⁽⁴⁾

Notes:

(1) In 10% H₂SO₄ solution at 102°C

(2) In 65% HNO₃ solution at 66°C

(3) In 5% HCl solution at 66°C

(4) At 20°C

3.2 Mixture of the Powders

3.2.1 Chemical composition of PTFE composites

Pure PTFE and seven different compositions of PTFE-based composites, listed in Table 3.6, were studied in this research. The content level of the fillers and the type of the fillers were carefully selected considering the industrial application of the bearings. It should be noticed that PTFE has a high compressibility; therefore, the volume percentage of PTFE decreases significantly after compaction while the volume percentages of the

fillers do not change considerably. Also, as discussed earlier, each of the fillers was added to PTFE to play a specific role or to improve some properties in the final materials such as wear resistance, mechanical properties, and the ability to work properly in different lubrication regimes. Specimen A was used to measure the properties of the pure PTFE and to certify that the fabrication parameters were selected properly. Composites B, C, and D were used to study the effect of Tribaloy alloy T-401 and its content level on the properties of PTFE. Composite E was fabricated to investigate the effect of incorporation of bronze particles on the properties of PTFE and it was used as a reference for composite F, G, and H. In the composites E, F, and G), the matrix and the filler content levels were kept constant (40% and 60% respectively) while the bronze content were partially replaced by other fillers in composite F, G, and H. The goal was to study the effects of the combination of two or more fillers on the properties of PTFE. Different fabrication techniques were tested to obtain desirable specimens. It is expected to develop a lead-free bearing material that meets the criteria for sliding bearing materials and is comparable or superior to the lead-base bearing materials.

Table 3.6 Chemical composition of PTFE and PTFE-based composites

A	100 (100)	0 (0)	0 (0)	0 (0)	0 (0)	-
B	90 (97.3)	10 (2.7)	0 (0)	0 (0)	0 (0)	-
C	80 (94.1)	20 (5.9)	0 (0)	0 (0)	0 (0)	-
D	70 (90.3)	30 (9.7)	0 (0)	0 (0)	0 (0)	-
E	40 (72.2)	0 (0)	60 (27.8)	0 (0)	0 (0)	-
F	40 (72.3)	15 (6.8)	45 (20.9)	0 (0)	0 (0)	-
G	40 (72.3)	20 (9.1)	40 (18.6)	0 (0)	0 (0)	-
H	41 (65.6)	12.5 (5)	40 (16.4)	1 (2.1)	5.5 (10.9)	PANEX® 35 CF, 1/8 inch length

3.2.2 Powder mixing

Teflon® 7C powder and fillers were mechanically mixed in a three dimensional Turbula type T2C mixer (Figure 3.2). It was observed that the Teflon® powder exhibited an unordinary behavior after one-hour mixing. Agglomeration occurred in the powder, which caused PTFE particles to stick together and form clustered balls during the mixing process. This happened due to the adhesive nature of the Teflon® powder, which is a granular moulding resin. Unfortunately, these clustered balls of Teflon® did not break throughout the mixing process; therefore, Teflon® in these balls could not be properly mixed with the fillers. As a result, some areas of unfilled PTFE can be observed in the specimens under a microscope, see Figure 3.3. To overcome the heterogeneous mixing of the powders, all the powder-form raw materials were screened with a sieve # 12 (1.68 mm sieve size) prior to the mixing step to get fluffy powders. In addition, the mixing step was split into two separate stages. At the first stage, the fluffy powders were mixed for 45 minutes. Then the mixed powders were screened by sieve # 18 (1 mm sieve size) and any lump was broken up. At the second stage, the mixture was put in the mixer again for 30 minutes. It was observed under the microscope that the powders were fully mixed and no area with inhomogeneity is present anymore, see Figure 3.4.

Figure 3.2 A three dimensional Turbula type T2C mixer

Figure 3.3 Unfilled areas of PTFE in a 30% T-401 filled composite

Figure 3.4 Fully mixed PTFE powder with 30% of T-401 filler

3.3 Fabrication Techniques

The technique used to fabricate composites has a significant effect on the final properties of the products. In this research, two different techniques were tested to obtain the specimens; they are compression moulding and hot isostatic moulding.

3.3.1 Compression moulding

Compression moulding is the predominant technique for fabrication of the basic shapes of PTFE granular resin composites. The required equipment for this technique includes a mould, a press, and a programmable oven. The technique consists of two main steps: preforming and sintering. The former is the initial pressing of a powder in order to form a compact while the latter is heating the powder at a high temperature until its particles adhere to each other.

3.3.1.1 Moulds

The moulds for compression moulding are commonly similar to those used for the powder metallurgy of metals. These moulds are generally made of chrome- or nickel-plated tool steels and consist of a main die with upper and lower end plates. The diameter and the height of the main die depend on the shrinkage and compression ratio of the resin respectively. Also, a minimum wall thickness is required for the die to avoid deformation during the moulding process. The following formula may be used to calculate the minimum required wall thickness [46]:

$$tm = Sa. \frac{p \times D}{2\sigma}, \quad (3-1)$$

where:

tm = Minimum wall thickness (mm),

p = Maximum internal pressure ⁽¹⁾ (N/mm²),

D = Inside diameter (mm),

σ = Allowable yield stress of the die material (N/mm²), and

Sa = Safety factor ⁽²⁾.

Notes:

(1) As a rule of thumb, it is equal to 0.7 of the specific preform pressure

(2) 2.5 is common practice

In the present work, two different cylindrical chrome-plated steel moulds with the die cross-sectional diameters of 49 mm and 31 mm were prepared. The bigger mould was used to make preforms with which tensile test specimens were fabricated, while the smaller mould was used to make the preforms for other tests such as wear and corrosion tests. The height and the thickness of both main dies are 97 mm and 7 mm respectively. The dies thicknesses comply with the minimum die thickness requirement assuming the yield strength of 200 MPa for the steel Grade 304.

3.3.1.2 Press

For compression moulding technique, a conventional hydraulic press, which is capable of exerting the required force (in accordance with the ASTM standards [14, 15]), is needed to make the preforms. This press should have good controls for smooth

pressure application and removal. In the present research, a hot mounting press of Struers Co. (laboPress-3), as shown in Figure 3.5, was used. Pressing parameters such as force, heating temperature, heating time, and cooling time are adjustable in the machine.

Figure 3.5 A laboPress-3 mounting press (Courtesy of Struers Co.)

3.3.1.3 Oven

The sintering oven for PTFE composites should be electrically heated, and programmable with a precise temperature controlling ($\pm 5^{\circ}\text{C}$ or narrower). There are two different types of sintering ovens, air-circulating ovens and inert-gas sintering ovens. The first type is more commonly used since these ovens are less expensive. However, composites sintered in this type of furnaces may have high porosity and low creep resistance due to the possible oxidization of the fillers. The second type is inert-gas sintering ovens, which are more expensive. Sintered preforms in this type of ovens have low void content and good creep resistance, but they have lower tensile strength [28]. In

the present research a programmable, electrical, inert-gas Oxygen oven (Figure 3.6) was employed to sinter the preforms.

Figure 3.6 An Oxygen inert-gas sintering oven

3.3.1.4 Preforming

In the process of preforming, pressure was applied to the PTFE moulding powder to get a compact with low void content and sufficient mechanical integrity for handling and sintering. Preforming started with mould filling, which has an important role in the quality of the final products. To avoid contamination of the powders, mould filling area and mould itself were cleaned with acetone prior to each filling process. Care was taken to fill the moulds uniformly, since improper mould filling could cause uneven densities, cracks, or distortions in the preforms. Therefore, a funnel was used in this step to

uniformly pour the powders into the moulds, with 5 mm of the top of the mould left unfilled. Successive partial charges and tamping to gain the designed fill height should be avoided, since they could lead to the contamination problem, charge to charge interface and possible cracking at the interfaces along the height.

Preforming is normally performed at room temperature. However, in the present research, the preforming temperature and heating time were set to be 150°C and 15 min respectively. The preforms were afterwards cooled down to room temperature by tap water in 15 min. Preforming at higher temperatures can compensate the press capacity limitation of the machine, because resin particles exhibit higher plastic flow at elevated temperatures [46], hence become more easily compacted and more responsive to preform pressure. Therefore, the final products preformed at higher temperatures usually exhibit lower void content and air-entrapment. A typical air-entrapment in a room-temperature-made preform is shown in Figure 3.7.

Figure 3.7 A view of air-entrapment in a preform

The maximum pressure used in preforming (preform pressure) has significant effects on the mechanical properties of the final products. The optimum preforming pressure is the pressure sufficient to give void-free preforms, but low enough to minimize preform stress and avoid plane slippage that may generate microcracks. According to the ASTM standards [14, 15] and the resin supplier's recommendations, the preform pressure was set to be 26.52 MPa that corresponded to 50 kN and 20 kN preforming forces for the big and small moulds respectively [14, 15, 46].

To avoid stress induced cracks, the maximum pressure should be applied smoothly. For this reason, 10% of the preform force was applied as initial load and held for 2 min. Then, the force was gradually increased up to the preform maximum pressure in 5 min. Since PTFE powder does not behave like an ideal fluid in compression, preforms should be held for a while at the maximum pressure. The purpose of this holding time, which is known as dwell time, was to increase the pressure distribution in the preform. Thus, the pressure decay was minimized and air-entrapments in the preforms could be avoided [47]. The dwell time in this research was selected to be 2 min. After that, the pressure was gradually released in 21 min and the preform was kept under 1 kN force during the cooling process. The pressure cycles for small and big preforms are presented in Figure 3.8 and Figure 3.9 respectively.

Figure 3.8 Pressure cycle for small size preforms

Figure 3.9 Pressure cycle for big size preforms

The mechanism of PTFE compression involves both plastic and elastic deformations. At low pressures, the particles are aligned into the best possible packing array by slipping and sliding. Once pressure is increased, contact points are established between adjacent particles and are enlarged with increasing pressure into distinct areas by plastic deformation. Internal particle voids are eliminated by plastic flow. Further pressure increase causes the elastic compression of the mass [46].

3.3.1.5 Sintering process

Sintering is the second step of the compression moulding process, in which preforms are converted to the objects with higher strength and lower void content. A time interval of two days between preforming and sintering was set as the resting time for preforms. This resting time was required for degassing and residual stress relief in the preforms before starting the sintering cycle. The preforms were then placed on a perforated tray to prevent any hot spots during the sintering and the tray was put into the oven. On start-up, the oven was purged with a high flow rate of argon gas to get an oxygen-free atmosphere. After that, sintering cycle was commenced. In this step, preforms were slowly heated to the peak sintering temperature and then gradually cooled down to room temperature. Selecting the peak sintering temperature, which is a temperature beyond the melting point of PTFE, depends on a complex interaction of many factors such as shape, size, and chemical composition of the preforms. An excessively high peak sintering temperature can cause thermal degradation in the resin, as shown in Figure 3.10; while an excessively low peak sintering temperature may result in poor mechanical properties of the sintered parts.

Figure 3.10 Resin degradation due to excessive high peak sintering temperature

During the heating period of the sintering cycle and prior to the melting of PTFE, resin particle coalescence and voids elimination occurred in the composites. On passing the melting point, PTFE changed from a solid material to a transparent gel. In this stage, contacting surfaces of adjacent particles fused to form a strong, dense, and void-free object [46].

When the melting and freezing transitions took place, the fast volume change could induce mechanical stresses, which resulted in cracking. Cracking problem may also occur due to excessive thermal gradients in the sintering objects. To avoid this problem,

both heating and cooling rates should be kept low. In addition, because of the low thermal conductivity of PTFE, some holding periods, especially at the peak sintering temperature, should be introduced in the sintering cycle.

In terms of the ASTM Standards (D 4894-04, and D 4745-06) and the resin manufacturer recommendations [14, 15, 28], the optimum heat-up rate, cooling rate, hold periods, and peak sintering temperature for each case were determined experimentally. In the present research, three different sintering cycles, illustrated in Figures 3.11 – 3.13, were designed; the heating and cooling rates were kept constant in the three cycles; however, holding periods and peak sintering temperatures changed among the preform geometries and chemical compositions. The peak sintering temperature and the dwell time for the specimens with 49 mm diameter were 375°C and 3.4 h respectively. Because of the big size of the specimens, these values were set to be higher than those of the small specimens to ensure sufficient sintering inside the billets. In addition, since thermal conductivity of PTFE was improved in the presence of fillers, a peak sintering temperature of 360°C and a holding period of 2.1 h were selected for small specimens with high content of fillers, while the values of 370°C and 2.5 h were used for designation A and B of small specimens.

Figure 3.11 Sintering cycle for big specimens (tensile testing specimens)

Figure 3.12 Sintering cycle for designations A and B of small specimens

Figure 3.13 Sintering cycle for all small specimens except designations A and B

Defects such as distortion, seen in Figure 3.14, and bubble, seen in Figure 3.15, in the sintered objects were abolished case by case, using the trial and error method. For instance, insufficient dwell time or too rapid cooling rate may cause uneven shrinkage or hourglassing in the specimens, while excessive pick sintering temperature or sintering time may cause melt flow or bubble in the sintered objects.

Figure 3.14 Distortion and hourglassing in sintered specimens

Figure 3.15 Bubble in sintered objects

3.3.2 Hot Isostatic Press Moulding

Hot isostatic pressing (HIP) is another technique used for fabrication of the PTFE composites. This technique also consists of preforming and sintering steps. To make a preform, a hydrostatic pressure at elevated temperatures is applied to a sealed flexible mould that contains the powder to be compacted. The pressure is then transmitted to the powder through the flexible mould and the powder becomes uniformly compacted. Similar to compression moulding, the next step is sintering. In this step, the preforms are sintered to develop structural integrity in the composites. This technique is usually used to make complex shapes with less pressure decay effect and machining cost. However, the cost of tooling and equipment is high compared with the compression moulding technique.

Round tubes of aluminum alloy 6063-T5, with 2.54 cm (1 inch) diameter and 0.16 cm (0.065 inch) wall thickness, were used for fabricating the specimens. These tubes were uniformly filled with the powders and then sealed at one end. The open end of each mould was connected to a vacuum hose to eliminate the possibility of trapping air in the pressed part, and then sealed and welded after two days. The sealed tubes were placed in a pressure vessel for HIPping. The vessel was pressurized to its maximum pressure, which was 103 MPa (15000 Psi), with the temperature to 290°C. After 24 hours and when it was depressurized, the vessel was opened and the moulds were placed in a sintering furnace. The same cycles as the compression moulding were used for sintering the preforms.

Unfortunately, the sintered objects did not have acceptable structural integrity. One possible reason might be the inadequate sealing of the moulds. Another explanation is the insufficient applied pressure at the preforming step. In this hypothesis, pressure was not enough to deform the aluminum moulds at 290°C and then compact the powders. However, this explanation does not seem acceptable since the yield strength of 6063-T5 aluminum alloys, with the same wall thickness as the used tubes and at 290°C, is 19 MPa (2.7 psi) [3]. Further investigation of the possible reason and the application of this technique will be the future work.

Chapter 4: Experimental Details

4.1 Microstructural Analysis

4.1.1 Specimen preparation

The first step of the microstructure analysis was specimen preparation. There was no need to cut or mount the specimens since they were prepared in the appropriate size by using a mounting press. The surface of each specimen was prepared by grinding and polishing operations. The details of these operations are presented in Table 4.1.

Table 4.1 The procedure of grinding and polishing operations [48]

CarbiMet abrasive discs	320-(P400) grit SiC water cooled	3 (13)	200 / Contra	Until Plane
CarbiMet abrasive discs	400-(P600) grit SiC water cooled	4 (18)	200 / Contra	0:30
CarbiMet abrasive discs	600-(P1200) grit SiC water cooled	4 (18)	200 / Contra	0:30
CarbiMet abrasive discs	800-(P1500) grit SiC water cooled	4 (18)	200 / Contra	0:30
TextMet 1000	3- μ m MetaDi II diamond paste and MetaDi fluid	5 (22)	200 / Contra	4:00
MasterTex Cloth	0.05- μ m MasterPrep alumina suspension	3 (13)	200 / Contra	4:00

A Buehler Ecomet-4 semiautomatic grinder polisher, shown in Figure 4.1, was used to perform these operations. The specimen holder of the machine is a fixed (rigid) frame. In this type of holders, pressure is applied on the specimens via the central column of the holder; therefore, it is necessary to place the specimens symmetrically to get flat surfaces after polishing operation.

Figure 4.1 The Buehler Ecomet-4 semiautomatic grinder polisher

Grinding operation was required to planarize the specimens for possible shrinkage due to the sintering. Although plastics and polymers are quite soft and can easily become

planar, it is required to carefully select the load and the speed of the grinding operation to minimize possible damages such as filler pull out of the composites. A 320 standard grit size of silicon carbide (SiC) abrasive paper was used with the operation parameters: a spindle speed of 200 rpm and a contact load of 3 N, according to the ASTM Standard E2015-04 and Buehler materials preparation guide [49, 50]. Water was used as the coolant to reduce the generated heat during grinding.

The purpose of polishing operation is to produce a bright mirrorlike, or specularly reflecting surface. Polishing operation consists of rough polishing and final polishing stages. Rough polishing is performed to eliminate the damage produced during planar grinding. As seen in Table 2.1, specimens were roughly polished with sequentially decreasing SiC abrasive paper grit sizes 400, 600, and 800; while water was used as the coolant. Final polishing is performed to remove surface damage only. In the present research, specimens were lightly polished with 3 μm diamond paste and 0.05 μm alumina suspension on two specific polishing pads. The specimens were thoroughly cleaned in an ultrasonic bath, prior and after each step of the final polishing since surface quality can be degraded by abrasion from the debris produced during polishing. After polished, the bronze filled specimens were etched with the solution of 95 ml ethyl alcohol + 5g ferric chloride + 10ml HCl to optically enhance microstructural features [48]. There was no need to etch the other specimens since it was easy to distinguish the shiny particles of T-401 or carbon fibers under a microscope.

4.1.2 Light microscopy

The images of microstructural features of the specimens were obtained with an Olympus PM-63 light microscope, shown in Figure 4.2. The microscope is capable of obtaining images in the magnification range of 5X to 100X.

Figure 4.2 The Olympus PM-63 optical microscope

4.1.3 Electron microscopy

The scanning electron microscope (SEM) is one of the most versatile instruments for investigating the microstructure of materials. An SEM has a greater resolution than a traditional optical microscope since it uses electrons instead of visible light that is used in optical microscopes. Also, because a SEM has a better depth of field than an optical microscope, the sharpness of the SEM images is much higher than that of the optical

images. In the present research, a Hitachi S-570 model, shown in Figure 4.3, of scanning electron microscope was used to produce the high-resolution images of the specimens' microstructures. The microscope is capable of obtaining images in the magnification range of 35X to 10000X and uses a tungsten filament thermionic emission gun as its electron beam emission source. Once cleaned and dried, the specimens were coated prior to mounting by a thin layer of graphite to become electrically conductive. This task was to prevent the accumulation of static electric fields on the specimen due to the electron irradiation required during imaging and also to improve the contrast of the image.

Figure 4.3 The Hitachi S-570 scanning electron microscope

4.2 Density Measurement

Immersion density technique was employed to determine the density of the specimens. This technique is based on Archimedes principles described as below:

- Weigh the specimen in air (w_d)
- Weigh the specimen in distilled water (w_{fl}) while suspended by thin wires

The following formula is used to calculate the density of the material [41, 55]:

$$\rho_k = \frac{w_d \cdot \rho_{fl}}{w_d - (w_{fl} - w_{wires} - w_{beaker})}, \quad (4-1)$$

where:

- ρ_k = specific density of the specimens,
 w_d = weight of the specimen in air,
 ρ_{fl} = density of distilled water,
 w_{fl} = weight of the specimen in distilled water,
 w_{wires} = weight of the wires, and
 w_{beaker} = weight of beaker.

The basic experimental apparatus, shown in Figure 4.4, is a Sartorius 6080 electronic balance, which is accurate to 0.1 mg and allows for both dry (at air) and wet (in bath) weighing of specimens. The setup includes a small metallic stand that fits into the balance and a small perforated plastic beaker that is suspended from the stand with two Kevlar wires. The beaker is submerged in a one-liter distilled water bath, allowing the specimen to be totally immersed while being measured. Care should be taken to avoid any contact between the beaker and wall of the water bath.

Figure 4.4 Density measurement setup

4.3 Corrosion Test

Bearings may be corroded by the acid introduced into the lubricants of engines by the combustion of sulfur containing fuels. In the present research, immersion testing was used to evaluate the corrosion resistance of the specimens. This test was intended to represent a worst-case situation rather than reproducing a certain environment or a specific condition of exposure. Therefore, the test medium was the oxidizing acid 65% HNO_3 at 65°C . Since corrosion is a surface phenomenon, the surface condition of the specimen is very important in the results of the tests [51]. In the present test, the surface of the specimens were polished to $0.05\ \mu\text{m}$ finish, cleaned in ultrasonic bath, and air-dried. The geometric area of each specimen was calculated to an accuracy of 1% and weighing of the specimens was accurate to 0.1 mg. The specimens then were immersed in

the corrosive solution for 72 h and were removed afterwards for examination. Shortly after removed from the medium, the specimens were properly cleaned by soft brushing under warm tap water to remove bulky deposits and corrosion products without significant removal of the base materials, and then the specimens were dried with ethanol and a blow dryer.

The mass loss of each specimen due to corrosion was determined by weighing the specimen before and after the corrosion test. To assess the corrosion damage, the average corrosion rates of the specimens were obtained according to the ASTM Standard G 1-03 [12] as below:

$$\text{Corrosion Rate} = (K \times M) / (A \times T \times \rho), \quad (4-2)$$

where:

$$K = 3.45 \times 10^6$$

T = time of exposure in hours,

A = area in cm^2 ,

M = mass loss in grams, and

ρ = density in g/cm^3 .

4.4 Hardness Test

Hardness represents the resistance of a material to permanent indentation. Due to the unique feature of PTFE materials, HRE and HRL Rockwell scales cannot be used to measure the hardness of the specimens in this study. For polymeric materials a durometer hardness tester, which is commonly used for plastics, can be employed. Durometer

hardness is an empirical test intended for control purposes and therefore, the hardness value determined by this test method does not necessarily correlate to other fundamental characteristics of the material tested [13]. The two most common scales of durometer are the A and D scales. The former is normally used for the softer plastics while the latter is used for the harder ones. In the present research, shore D scale was used to report the hardness of all the specimens.

The test apparatus was a manual shore instrument of MFG. INC. Co., shown in Figure 4.5. The specimens were 10 mm (2.54 in.) in thickness and 31 mm (1.22 in.) in diameter, and had flat surfaces. Tests were conducted in accordance with the ASTM Standard D 2240-05 in the standard laboratory atmosphere, as defined in ASTM Standard D 618-05 [13, 52].

Figure 4.5 Manual shore hardness instrument (Courtesy of MFG. INC. Co)

4.5 Tensile Test

4.5.1 Procedure

Tensile tests were performed to measure the mechanical properties of the specimens. The stress – strain curve of each specimen was obtained using a MTS 858 (load capacity 25 kN) testing apparatus, shown in Figure 4.6, with the constant rate-of-crosshead movement according to the ASTM Standard D 638M-93 [17]. Serrated face grips were used to avoid slippage of the specimens during the tests. Care should be taken when using this type of grips to avoid any yielding or tearing of the specimen at the grips. The specimens were clamped in an equal length at each jaw. The tests were conducted in the standard laboratory atmosphere with a loading rate of 13 mm (0.5 in.) / min.

Figure 4.6 The MTS 858 tensile testing apparatus

Microtensile specimens, shown in Figure 4.7, were made from the developed materials for the tensile test in accordance with the ASTM Standards D 1708-06a [16], D 4894-04 [14], and D 4745-06 [15]. These specimens, which are only used for determination of the tensile properties of plastics, were prepared by machining from the big sintered specimens (49 mm diameter billets) and conformed to the dimensions in Figure 4.8. The reason for using the microtensile specimens lies in the high compressibility of the PTFE powder. A mould length of 250 mm (9.8 in.) produces a billet approximately 75 mm (2 to 3 in.) long [15]. Therefore, due to the limitation of the hydraulic press capacity, it was impossible to use any other types of specimens, which complies with the ASTM Standard D 638M-93 [17].

Figure 4.7 Microtensile specimens

$$El = \frac{F - I}{I} \times 100, \quad (4-3)$$

where:

El = elongation, %,

F = final length of the jaw separation, mm, and

I = initial length of the jaw separation, mm.

3. Young's modulus: The modulus of elasticity (E) of each specimen was calculated in the way that the tensile stress was divided by the corresponding tensile strain in the linear range. The results were then expressed in gigapascal (GPa).

4.6 Wear and Friction Tests

4.6.1 Apparatus

Tribological properties are important for sliding bearing materials; therefore, the tribological behaviors of the developed polymeric materials were investigated using a TEER-POD-2 computer controlled pin-on-disk tribometer, shown in Figure 4.9 – 4.10.

Figure 4.9 Sketch of the friction pair for the sliding contact

Figure 4.10 TEER-POD-2 computer controlled pin-on-disk tribometer

4.6.2 Specimens

Sliding wear refers to a type of wear generated by the sliding of one solid surface along another surface [1]. Therefore, in a pin-on-disk test, two specimens are required which are known as pin and disk. The pin used in this research is a 5 mm diameter AISI 52100 steel ball provided by TEER Coating Limited, with the hardness of 60-67 HRC, which equates to between 697 and 900 Vickers. The pin was positioned perpendicular to a flat surface known as disk. The disks, those are, the tested specimens, were sintered billets with 31 mm diameter and 10 mm thickness. These specimens were polished to 0.05 μ m finish, cleaned in an ultrasonic bath, and then dried. The weights of the polished, cleaned, and dried specimens were measured to an accuracy of 10^{-4} g before the wear test.

4.6.3 Test parameters

The tests were conducted under a dry-lubricating condition and in accordance with ASTM Standard G 99-05 [18]. The test parameters are:

- Load: 10 N, the value of force at the wearing contact.
- Speed: 0.1 m/s selected as the relative sliding speed between the contacting surfaces.
- Time: 83 min, the duration of each test.
- Distance: ~ 500 m, the accumulated sliding distance within the period of wear test, calculated from the time and the speed.
- Atmosphere: The tests were conducted in the standard laboratory atmosphere with the relative humidity of 40% and the temperature of 23°C.

4.6.4 Calculation and reporting

Three types of data were obtained from the pin-on-disk tests:

- Wear loss: After the test, the disk specimens were cleaned by soft-brushing under warm tap water to remove debris generated during the wear test, dried, and weighed to an accuracy of 0.0001g. Assuming that there was no significant pin wear, the following equation was used to calculate the volume losses of the specimens due to the wear [18]:

$$\Delta V = \frac{m}{\rho} \times 1000, \quad (4-4)$$

where:

ΔV = volume loss, mm³

m = mass loss, g, and

ρ = density, g/cm³.

- Wear factor: Using the formula expressed below, the wear factor or the specific wear rate of each specimen was obtained [18]:

$$k = \frac{\Delta V}{F \cdot \Delta s}, \quad (4-5)$$

where:

k = specific wear rate,

ΔV = volume loss, mm³

F = normal force, N, and

Δs = sliding distance, m.

- Friction coefficient: The coefficient of friction (μ) of each specimen was recorded automatically throughout the test with the aid of a linear variable displacement transducer so that the variation of the friction coefficient with time can be obtained.

To understand the wear mechanism of the PTFE composites and investigate the effect of the fillers on the friction and wear behavior of the composites, the worn surfaces of all the specimens were studied using an optical microscope and SEM.

Chapter 5: Results and Discussion

5.1 Microstructures

The images of the microstructures of each specimen under an optical microscope and under a scanning electron microscope are presented in Figure 5.1 to Figure 5.8. Pure PTFE looks grayish optically. Since T-401 particles were not etched, they look shiny in the micrographs and can be distinguished from bronze particles, which were etched and become blurry. The micrographs of the PTFE composites show that the fillers were fully mixed with the matrix and no area with inhomogeneity was observed. In Figure 5.6 it can be seen that some fillers were pulled out during the rough polishing step. Since no voids are found in the microstructures and the fillers are embedded in the PTFE matrix very well, it can be inferred that the fabrication parameters such as preforming pressure and sintering cycles were selected properly.

Figure 5.1 Microstructure of specimen A

Figure 5.2 Microstructure of specimen B

Figure 5.3 Microstructure of specimen C

Figure 5.4 Microstructure of specimen D

Figure 5.5 Microstructure of specimen E

Figure 5.6 Microstructure of specimen F

Figure 5.7 Microstructure of specimen G

Figure 5.8 Microstructure of specimen H

5.2 Densities

Table 5.1 presents the results of the density test of pure PTFE and seven different PTFE composites. The density of water at room temperature is assumed to be 1 g/cm^3 . The density of the specimen A complies with what was reported in previous research [28] for a pure PTFE specimen produced with the same process. Since polymers are lightweight materials, pure PTFE has the lowest density. As expected, the densities of the composites are higher than that of the virgin PTFE because fillers are much denser than the matrix. Also, composite G has the highest density since it contains 40% of bronze and 20% of the dense T-401 filler.

Table 5.1 Specific densities

A	2.17 (0.0784)
B	2.41 (0.0871)
C	2.62 (0.0946)
D	2.85 (0.1030)
E	3.85 (0.1391)
F	3.92 (0.1416)
G	3.93 (0.1420)
H	3.00 (0.1084)

5.3 Corrosion Resistance

The corrosion rates of all specimens in mils per year are illustrated in Figure 5.9.

Figure 5.9 Corrosion resistance

It is demonstrated that the corrosion rate of PTFE increases when it is filled with the fillers. However, even the corrosion resistance of the composite H, which has the highest corrosion rate among the specimens, is much better than what is expected for a typical life of a bearing. The high corrosion resistance of the developed composites is because of the excellent corrosion resistance of both the matrix and the fillers. It should be noticed that in a real situation bearings are not subjected to such a highly corrosive environment. Therefore, the aim of the performed tests is to demonstrate the excellent

corrosion resistance of the developed composites rather than duplicating a practical condition of exposure.

There are two mechanisms involved in the corrosion of PTFE composites, aqueous corrosion (surface oxidation) and galvanic corrosion. Aqueous corrosion happens because of the electrochemical process occurring at the interface between the fillers and the corrosive media [51]. Galvanic corrosion occurs since fillers with differing surface electrical potentials are in electrical contact with each other in the conductive corrosive media [53]. In the single-filler composites (B, C, D, and E), the corrosion rate was increased by increasing the filler content. This can be attributed to the more surface oxidation due to the more filler content. In bi-filler and quad-filler composites (F, G, and H), because of the potential difference existing between dissimilar fillers, galvanic corrosion also occurs in combination with the surface oxidation of the fillers, which leads to the higher corrosion rates. Comparing composites F and G, it is proved that bronze is cathodic to T-401 since with increasing the content of T-401 in composite G, the corrosion rate is increased, which can be attributed to the increase in the corrosion rate of T-401 and decrease in that of the bronze. Another reason for the higher corrosion rate of composites H would be its higher void content. Since acid may be introduced into these voids, the interface between the fillers and the corrosive media becomes larger, leading to the higher corrosion rate.

5.4 Durometer Hardness

According to the ASTM Standard D 2240-05, seven determinations of hardness at different positions on each specimen were performed and an average of these seven results was reported as the shore hardness of the specimen. The hardness results are presented in Figure 5.10. Since the hardness of the specimen A complies with the hardness value of pure PTFE reported by previous research, in Table 2.1, the reliability of the specimen fabrication method and the hardness test results can be proved. It is seen that the hardness of PTFE is increased (up to 17%) by the addition of fillers. In particular, composite G exhibits the maximum hardness (67.91 shore D). It is also observed that the hardness values of the PTFE composites increase with the increase of the proportion of the fillers. Furthermore, the hardness of the fillers is another factor that affects the hardness of the composites. Although the filler content in specimen H is much more than that in specimen D (59% and 30% respectively), their corresponding hardness values are close to each other. This behavior is due to the fact that the presence of the hard particles in composite D is more compared with composite H. In other words, specimen D contains 70% of soft phase of PTFE, while specimen H contains 86.5% of the soft and semi-soft phases of PTFE, graphite, and bronze.

Figure 5.10 Durometer hardness

5.5 Mechanical Behaviors

5.5.1 Stress – strain curves

For each material, at least five specimens were tested under standard tension. The specimens that did not break within the range of the strain gauge were discarded. The stress-strain curves obtained from the tensile tests are presented in Figure 5.11 to 5.18.

Figure 5.11 Stress-strain curve of specimen A

Figure 5.12 Stress-strain curve of specimen B

Figure 5.13 Stress-strain curve of specimen C

Figure 5.14 Stress-strain curve of specimen D

Figure 5.15 Stress-strain curve of specimen E

Figure 5.16 Stress-strain curve of specimen F

Figure 5.17 Stress-strain curve of specimen G

Figure 5.18 Stress-strain curve of specimen H

5.5.2 Discussion of the mechanical properties

The mechanical properties of all the specimens obtained from the tensile tests and calculated from the stress – strain curves, are presented in Table 5.2. The tensile properties of specimen A (pure PTFE) is in agreement with the properties reported by the resin manufacturer (Tables 2.2 and 3.1). Therefore, it can be assumed that the specimen fabrication parameters were selected properly.

Table 5.2 Mechanical properties of the specimens

A	24.93	27.99	26.93	665	0.77
B	15.03	21.02	20.04	385	0.95
C	14.01	19.25	18.47	480	1.21
D	14.48	18.4	17.56	427	1.27
E	14.85	16.87	16.67	101	1.65
F	14.83	18.09	17.14	147	1.67
G	15.66	18.28	17.54	155	1.90
H	8.8	13.03	10.08	101	1.06

Considering the percentage elongation at break of each specimen, it can be seen that the ductility of PTFE decreases with the addition of the fillers. No localized necking was observed in virgin PTFE in particular, and also in specimens B, C, and D. Instead, these specimens were drawn uniformly through the gauge length; see Figure 5.19, until they broke. Therefore, high strains with substantial strain hardenings were recorded in these specimens.

Figure 5.19 Uniformly drawn specimens with no necking:
(a) Specimen A, (b) Specimen C

It is demonstrated that the filled compounds of PTFE have higher Young's modulus but lower tensile strength than pure PTFE. This behavior is consistent with what have been reported by other researchers [28, 54]. The tensile strength of a composite mainly depends on the interfacial adhesion between the matrix and the reinforcements since the stress must be transferred from the matrix to the reinforcements through the interface. Because the bond between the fillers and PTFE is strictly mechanical rather than chemical, there is a lack of strong adhesion at the interfaces. As a result, PTFE filled compounds exhibit lower tensile strengths than virgin PTFE since the stresses cannot be effectively transmitted from the resin to the fillers.

For the PTFE composites, the results show that the ultimate strength is a function of both the content level of the fillers and the type of the fillers. It was observed that in specimens B, C, D and E, the ultimate strengths were decreased by 20% at most with increasing the content level of the fillers. In addition, compared with the specimen E, the

ultimate strengths of specimens F and G in which the bronze contents were partially replaced by T-401 (it is harder than bronze), were respectively improved by 7% and 8%. Composite H has the poorest tensile properties among all the specimens. Although the provided bundled carbon fibers with the shortest length were used in this composite, it is believed that these fibers are still too long to be impregnated by the high viscose PTFE resin. Therefore, there were some areas between the carbon fibers that were not fully impregnated by resin. Thus, stress concentration would occur at the sharp corners of these void areas where cracks are initiated, leading to failure of the material.

Regarding the Young's modulus values, it is clear that these values are also a function of the content level of the fillers and the type of the fillers. Comparing the specimens A, B, C, D and E, it can be inferred that the Young's modulus values of the composites increase by increasing the filler content since the hardness of the fillers is much higher than that of the resin. However, it should be noticed that higher filler content means more interfaces between the matrix and the reinforcements. Since the bonds between the fillers and the matrix are not very strong in the composites, these interfaces become the places for crack initiation, which results in the lower ultimate strength. In addition, comparing the specimens E, F and G, the type of fillers and more specifically the hardness of fillers can affect the Young's modulus of the composites. It is shown that the Young's modulus values of the composites are increased by increasing the hardness of the fillers.

5.6 Tribological Behaviors

5.6.1 Friction coefficients

Friction coefficient is the most important parameter for sliding bearing materials, as discussed in Chapter 2. In this research, the friction coefficients of the developed PTFE materials were determined during the pin-on-disc wear tests. These values were calculated by the machine software and were recorded automatically. The obtained results are presented in Figure 5.20, which show the variations of the friction coefficients with the sliding time.

As shown in this Figure, the friction coefficient, μ , goes up at the initial stage and is followed by a narrow peak; then it becomes constant with a lower value. The constant values of friction coefficient for all the tested materials vary in a range of $0.1 < \mu < 0.16$ after 45 min sliding. As illustrated in Figure 5.21, adding the fillers to PTFE changes the friction coefficient of PTFE only marginally. This behavior, which is in agreement with the analysis made by other researchers [5, 7, 32, 33], is attributed to the presence of a thin transfer film of PTFE on the counter surface, which enables PTFE composites to maintain almost the same frictional properties as pure PTFE.

Figure 5.20 Frictional behaviors of all the specimens

It is also demonstrated that the coefficient of friction is more dependent on the filler content rather than the type of fillers. As seen in Figure 5.21, μ is increased by increasing the amount of the filler in specimens B, C, D and E, while it becomes almost constant for specimens E, F, G and H in which the content level of fillers is almost constant (60%); however, different types of fillers are used.

Figure 5.21 Comparison of the frictional characteristics of all the specimens

5.6.2 Wear rates

The wear losses of materials are represented by the volume losses of the specimens during the wear tests, as illustrated in Figure 5.22. The specific wear rates are illustrated in Figure 5.23.

Figure 5.22 Volume losses due to sliding wear

Figure 5.23 Specific wear rates

5.6.3 Worn surfaces

The images of the worn surfaces obtained by optical microscopy and SEM microscopy are presented in Figures 5.24 – 5.31. It can be observed that the widths of the wear tracks of the composites are much less than that of the pure PTFE. Also, an excessive filler concentration can be seen on the wear tracks of the composites. Furthermore, the size of the wear fragmentation is much less in PTFE composites compared with the unfilled PTFE.

(a)

(b)

Figure 5.24 Worn surface images of specimen A:
(a) Optical microscopy, (b) SEM image

(a)

(b)

(c)

Figure 5.25 Worn surface images of specimen B:
(a) Optical microscopy, (b) SEM image, (c) SEM image of wear fragmentation size

(a)

(b)

Figure 5.26 Worn surface images of specimen C:
(a) Optical microscopy, (b) SEM image

(a)

(b)

(c)

Figure 5.27 Worn surface images of specimen D:
 (a) Optical microscopy, (b) SEM image (c) SEM image of wear fragmentation size

(a)

(b)

Figure 5.28 Worn surface images of specimen E:
(a) Optical microscopy, (b) SEM image

(a)

(b)

Figure 5.29 Worn surface images of specimen F:
(a) Optical microscopy, (b) SEM image

(a)

(b)

Figure 5.30 Worn surface images of specimen G:
(a) Optical microscopy, (b) SEM image

(a)

(b)

Figure 5.31 Worn surface images of specimen H:
(a) Optical microscopy, (b) SEM image

5.6.4 Discussion

As can be seen in Figures 5.22 and 5.23, the high wear rate of PTFE is reduced dramatically by adding the fillers. The results show that the addition of the filler materials can cause a remarkable improvement (up to one order of magnitude) in the wear resistance of PTFE. Composite F exhibits the highest wear resistance amongst all the composites with a specific wear rate of $2.6 \cdot 10^{-5} \text{ mm}^3/\text{N.m}$.

The wear behaviour of PTFE compounds has been found to be a complex phenomenon, which depends upon many factors. These factors include the nature of the fillers, the content level of the fillers present and their morphology.

5.6.4.1 Effect of the filler nature

The nature of the filler that includes its coefficient of thermal conductivity, hardness, load carrying capability, and obstructing large-scale fragmentation ability, plays the most significant role in the wear behaviour of PTFE composites.

1. **Filler thermal conductivity:** The maximum load that can be carried by a bearing and its adhesive wear resistance are somehow related to the rate at which heat developed through friction can be dissipated [4, 7, 28]. Therefore, due to its low thermal conductivity, pure PTFE has a very low bearing capacity and high adhesive wear rate. This is because PTFE matrix loses its integrity under severe wear conditions (high load and high velocity) since the large amount of heat developed during the rubbing process of the sliding surfaces cannot be properly dissipated. Also, excessive heat may cause expansion of the shaft, housing, or

bearing. This expansion reduces the clearance between the shaft and the bearing, resulting eventually in premature bearing failure. However, the very low thermal conductivity of PTFE can be significantly improved by incorporation of fillers such as T-401 and in higher extent, with bronze, graphite and carbon fibres, because these fillers have larger thermal conductivity. It might be because of such mechanism (improvement in thermal conductivity) that the wear resistance of the developed PTFE composites is drastically improved. The further investigation of such mechanism needs to measure the thermal conductivity of each specimen and will be the future work.

2. **Filler hardness:** Due to the chemical inertness of PTFE, there is no strong chemical bond between the fillers and the matrix; therefore, some of the fillers may pull out from the PTFE matrix during bearing operation and come into the rubbing surfaces. Thus, in addition to the adhesive wear, abrasive wear may also occur due to the presence of these fillers, which induces wear debris. The wear debris may consist of particles of PTFE, fillers, and the mating surface. Since PTFE particles are very soft, they scratch neither the bearing nor the shaft, but they increase the lubricity of the bearing during the operation as solid lubricants. On the contrary, the debris of the fillers and the mating surface can cause scratching both on the shaft and the bearing itself. Furthermore, the transferred film of PTFE that provides the desirable frictional properties of the resin can be easily removed or worn by these types of debris when sliding continues. Therefore, the degree of the surface damage to the bearing and its counterface, and the durability of the transfer film depend on the relative hardness of the

fillers, PTFE, and the shaft and the ability of the matrix to bury the debris in its soft surface. Unfortunately, the wear of the shaft due to abrasion was not generally considered by other researchers. It should be noticed that wear is a phenomenon happening on two mutually interactive materials. In other words, bearings are not only subjected to wear themselves, but they abrade the mating surface as well. Although the wear rate of PTFE materials can be reduced by the addition of hard fillers, the mating surface may become severely worn due to abrasion. One of the advantages of the newly developed composites is that their mating surfaces do not suffer from abrasion since no pin-wear was observed under the microscope. It is expected that the bearings fabricated by the developed composites show good compatibility since in these composites less abrasive materials such as T-401 and bronze, which have the hardness values between the hardness of the matrix and its mating surface, were used as the fillers. These fillers are hard enough to polish any asperities on the counterface without being able to scratch it. This optimal hardness leads to the higher shaft lifespan in light of the fact that the pulled out fillers cannot scratch the shaft. In the meanwhile, longer bearing lifetime is expected since no more hard debris of the shaft exist to abrade the PTFE bearings. In addition, the transfer film of PTFE can be effectively preserved so that the wear rate of PTFE is controlled since no more cyclic formation and destruction of this film occur. Finally, the good conformability and embeddability can be also achieved, especially in composite F, due to the presence of soft and semi-soft phases of PTFE and bronze respectively,

while harder particles of T-401 provide the bearing with some other required criteria, for example, wear resistance.

3. **Load support:** The load capacity of a bearing is defined as the maximum unit pressure under which the material can operate without excessive friction or wear damage [1]. The excess filler concentrations on the wear tracks of the filled compounds, which can be seen in Figures 5.25 to 5.31, may be attributed to the preferentially load supporting mechanism of the fillers. It seems that the load supporting role of the Tribaloy particles is more than that of the bronze particles since the wear properties of the composite E is improved by 50 % when bronze particles are partially replaced by T-401 particles in composite F. However, comparing composites F and G, it is observed that when replacing the bronze with T-401 over a specific amount, the influence of the filler thermal conductivity mechanism on reducing wear is more significant than that of the preferentially load supporting mechanism since the wear rate of specimen G is increased with increasing the T-401 content to 20%.
4. **Obstructing large-scale fragmentation:** The worn micrographs of the specimens show that the wear-reducing role of the fillers can also be a preventive one in light of the severe wear that is induced without the fillers. As seen in Figures 5.24 to 5.31, the width of the wear scar of virgin PTFE is reduced by up to 53 % in composite F. In addition, it is observed that the production of larger wear particles is prevented by all the types of fillers. As a result, the worn surfaces of PTFE composites are much smoother than that of the virgin PTFE. Therefore, reduced wear rate of the filled compounds of PTFE can also be attributed to the abilities of

the fillers in controlling the size and the shape of the wear fragments. This is evident from the small size of the wear debris of the PTFE composites, which were measured in the micrographs, see Figures 5.25 (c) and 5.27 (c). Thus, it can be concluded that the fillers act as effective barriers to prevent large-scale fragmentation of PTFE, resulting in formation of small and discontinuous fragments and consequently lowering the wear rates.

5.6.4.2 Effect of the filler content

Effect of the filler content on the wear resistance can be investigated by comparing samples B, C and D. It is shown that the wear resistance of these PTFE composites is improved (up to 58%) by increasing the content level of the T-401 filler from 10% to 30%. This behaviour can be attributed to the ability of the Tribaloy particles in reducing wear with the mechanisms discussed above.

5.6.4.3 Effect of the filler morphology

The wear resistance of the PTFE composites was also influenced by the morphology of the fillers. Considering composite H, it was observed that incorporation of the very fine filler particles such as tiny particles of graphite could lead to higher wear rate. This is in agreement with what was reported in the references [27, 33] that compounds filled with particles which are similar in size to those of the base resin itself exhibited the highest wear resistance. In addition, while theoretically adding carbon fibres with high aspect ratio can increase the mechanical and tribological properties of the resin, long fibres, especially when they are in the bundle form, may cause a problem because

the whole length of fibres cannot be completely impregnated by the high viscous PTFE resin.

Chapter 6: Conclusions and Future Work

6.1 Conclusions

Based on the experimental results and the discussion, the following conclusions can be drawn from this research.

1. The corrosion rate of PTFE increases when it is filled with fillers. Since the selected fillers are corrosion resistant, the corrosion rate of the developed composites remains very low, which is much better than what is expected for the typical life of a sliding bearing.
2. Addition of T-401, bronze and carbon fiber filler to PTFE enhances the hardness up to 17%. The hardness of a PTFE composite is affected by the content level of the fillers and the hardness of the fillers as well.
3. The ductility of PTFE decreases when it is filled with the fillers. Under tensile testing, no localized necking was observed in pure PTFE and in the composites filled with T-401 only (specimens B, C, and D). Instead, these specimens were drawn uniformly until they broke. Therefore, high strain with strain hardening was recorded in these specimens.

4. The filled compounds of PTFE have lower tensile strength than pure PTFE.

The reason for such behavior is that the bond between the fillers and PTFE is strictly mechanical rather than chemical; therefore, there is a lack of strong adhesion at the interfaces. As a result, PTFE filled compounds exhibit lower tensile strengths than pure PTFE since the stresses cannot be effectively transmitted from the resin to the fillers.

5. The ultimate strength of the PTFE composites is mostly a function of the content level of the fillers. It was observed that increasing the content level of the fillers in the PTFE composites decreases their ultimate strength. Also, the hardness of the fillers can affect the ultimate strength of the PTFE composites. Between two composites with the same content level of the fillers, the one which was filled with the harder fillers has higher ultimate strength.

6. Adding the fillers to PTFE changes the friction coefficient of PTFE only marginally. This behavior is attributed to the presence of a thin transfer film of PTFE on the counter surface that enables the PTFE composites to maintain almost the same frictional properties as pure PTFE. Also, the coefficient of friction is more dependent on the filler content (μ is increased by increasing the amount of the filler in the composites) rather than the type of fillers.

7. Addition of the filler materials significantly improves the wear resistance of PTFE. The wear behaviour of PTFE compounds is a complex phenomenon,

which depends on the nature of the fillers, the content level of the fillers present, and their morphology.

8. Among the developed composites, composite F has the best combination of tribological, mechanical, and anti-corrosion properties. Exhibiting a yield tensile strength of about 15 MPa, which is 50% higher than the best reported yield strength of the existing PTFE composites. As a corrosion resistant sliding bearing material, composite F maintains the excellent antifriction property of PTFE, while its wear resistance is improved by one order of magnitude compared with pure PTFE.

6.2 Future work

Following the investigations described in this thesis, a number of projects could be recommended for the future work, which will be performed by the author during the PhD study:

1. Further study of the compression moulding technique with different preforming parameters such as preforming pressure, temperature, and heating-cooling times
2. Testing of other fabrication techniques such as double sintering-double pressing, and hot isostatic moulding
3. Investigation of the effects of the filler aspect ratio on the final properties of PTFE composites by using non-bundle carbon fibers

4. Study of other compositions of PTFE composites such as 45% PTFE + 10 % T-401 + 45% bronze, 50 % PTFE + 10 % T-401 + 40 % bronze, and 55% PTFE + 7% T-401 + 35% bronze +2% graphite + 1% carbon fiber, to obtain more information on the best PTFE composite with improved mechanical and tribological properties
5. Investigation of the application of PTFE aqueous dispersion to coat the shaft with the developed PTFE composites
6. Performing fatigue test to measure the ability of the developed composites to withstand properly in cyclic loads
7. Examination of the tribological properties of the developed PTFE composites when they are subjected to higher loads, slide at higher speeds, and slide for longer times
8. Measuring the thermal conductivity of the developed composites in order to prove the theory of wear improvement due to the improvement in the heat dissipation property of PTFE when it is filled with fillers with high thermal conductivity
9. Improvement in the tensile properties of the developed composites using LaCl_3 as a rare earth surface treatment material

10. Manufacturing the bearing components such as bearing pads and bearing liners with the developed composite F and testing them statically and dynamically

References

- [1] ASM Handbook Committee, “Friction, Lubrication, and Wear Technology”, Vol. 18, ASM International, USA, 1992.
- [2] X. Ai and Ch. A. Moyer, “Modern Tribology Handbook”, Vol. I & II, CRC Press, 2001.
- [3] ASM Handbook Committee, “Properties and Selection: Nonferrous Alloys and Special-Purpose Materials”, Vol. 2, ASM International, USA, 1990.
- [4] X. Cheng and Q. Shang-guan, “Effect of Rare Earths on Mechanical and Tribological Properties of Carbon Fibers Reinforced PTFE Composite”, Tribology Letters Journal, Vol. 21, No. 2, Feb. 2006, pp. 153-60.
- [5] F. Li, K. Hu, J. Li, and B. Zhao, “The Friction and Wear Characteristics of Nanometer ZnO Filled Polytetrafluoroethylene”, Wear Journal, Vol. 249, Issue: 10-11, Nov. 2001, pp. 877-82.
- [6] Z. Zhang, W. Liu, Q. Xue, and W. Shen, “Friction and Wear Characteristics of PTFE Composites Filled with Metal Oxides Under Lubrication by Oil”, Journal of Applied Polymer Science, Vol. 66, No. 1, Oct. 1997, pp. 85-93.

- [7] J. Khedkar, I. Negulescu, and E. Meletis, "Sliding Wear Behavior of PTFE Composites", *Wear Journal*, Vol. 252, No. 5, Mar. 2002, pp. 361-9.
- [8] C. Speerschneider and C. Li, "The Role of Filler Geometrical Shape in Wear and Friction of Filled PTFE", *Wear Journal*, Vol. 5, 1962, pp. 392-9.
- [9] B. J. Briscoe and M. D. Steward, "The Effect of Carbon Aspect Ratio on the Friction and Wear of PTFE", *Wear Journal*, Vol. 42, No. 1, 1977, pp. 99-107.
- [10] K. Tanaka and S. Kawakami, "Effect of Various Fillers on the Friction and Wear of Polytetrafluoroethylene-Based Composites", *Wear*, Vol. 79, No. 2, Jul. 1982, pp. 221-34.
- [11] R. Liu, W. Xu, P.C. Patnaik, M.X. Yao, and X.J. Wu, "Mechanical and Tribological Properties of Newly Developed Triballoy Alloys", *Materials Science and Engineering A*, Vol. 452-453, Apr 15, 2007, pp. 427-36.
- [12] ASTM Standard Committee, "Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens", (G 1-03), ASTM International, USA, 2007.
- [13] ASTM Standard Committee, "Standard Test Method for Rubber Property—Durometer Hardness", (D 2240-05), ASTM International, USA, 2005.

- [14] ASTM Standard Committee, “Standard Specification for PTFE Granular Molding and Ram Extrusion Materials”, (D 4894–04), ASTM International, USA, Mar. 2004.
- [15] ASTM Standard Committee, “Standard Specification for Filled Compounds of PTFE Molding and Extrusion Materials”, (D 4745–06), ASTM International, USA, 2007.
- [16] ASTM Standard Committee, “Standard Test Method for Tensile Properties of Plastics by Use of Microtensile Specimens”, (D 1708-06a), ASTM International, USA, 2006.
- [17] ASTM Standard Committee, “Standard Test Method for Tensile Properties of Plastics (Metric)”, (D 638M-93), ASTM International, USA, 1993.
- [18] ASTM Standard Committee, “Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus”, (G 99-05), ASTM International, USA, 2005.
- [19] T. Harris and M. Kotzalas, “Advanced Concepts of Bearing Technology”, Fifth Edition, CRC Press, Boca Raton, FL, USA, 2007.
- [20] P. Eschmann, L. Hasbargen, K. Weigand, and J. Brandlein, “Ball and Roller Bearings”, John Wiley & Sons Ltd. 1985.

- [21] Al. Nica, “Sliding Bearings”, Allerton Press, Inc., NY, USA, 1985.
- [22] R. J. Welsh, “Plain Bearing Design Handbook”, The Thetford Press Ltd., UK, 1983.
- [23] M. J. Neale, “The Tribology Handbook”, Second Edition, Antony Rowe Ltd., Oxford, Britain, 2001.
- [24] E. R. Booser, “Plain Bearing Materials”, Machine Design, 42(15), 1970, pp. 14–20.
- [25] S. Shiao and T. Wang, “Dry Self-Lubricating Composites”, Composites Part B (Engineering), Vol. 27B, No. 5, 1996, pp. 459-65.
- [26] M. Fujita, “Surface Alteration of Lead Free Automotive Engine Bearings”, Machine Design, Nikkan Kogyo Ltd, Japan, 2004, pp. 42-5.
- [27] “Handbook of Industrial Materials”, Elsevier Advanced Technology, UK, 1992.
- [28] “Filled Compounds of Teflon PTFE”, DuPont, USA, 2006.

- [29] H. I. Rowan, "ASM International Engineered Materials Handbook-Engineering Plastics", Vol. 2, ASM International, USA, 2001.
- [30] S. Ebnesajjad, "Fluoroplastic", Plastics Design Library, Norwich, NY, USA, 2000.
- [31] M. Jones, "PTFE Plain Bearings", Industrial Lubrication and Tribology Journal, Vol. 48, No. 6, 1996, pp. 10-2.
- [32] D. Landheer, C. Meesters, and M. Noort, "A Tribological Characterization of Teflon PTFE Compounds", DuPont Technical Information, 2006.
- [33] T. Blanchet and F. Kennedy, "Sliding Wear Mechanism of Polytetrafluoroethylene (PTFE) and PTFE Composites", Wear Journal, Vol. 153, No. 1, Mar. 1992, pp. 229-43.
- [34] S. Bahadur and D. Tabor, "The Wear of Filled Polytetrafluoroethylene", Wear Journal, Vol. 98, Nov. 1984, pp. 1-13.
- [35] M. D. Steward, "The Wear of PTFE Composites", Ph.D. Thesis, University of Cambridge, 1978.

- [36] G. Pocock and P. Cadman, "The Application of Differential Scanning Calorimetry and Electron Spectroscopy to PTFE-Metal Reactions of Interest in Dry Bearing Technology", *Wear*, No. 37, 1976, pp. 129 – 41.

- [37] M. Donachie and S. Donachie, "Superalloys, A Technical Guide", Second Edition, ASM International, USA, 2002.

- [38] A. Beltran, E. Brown, W. Chambers, and D. Chang, "Superalloys II", Wiley Inc., New York, USA, 1987.

- [39] Y. Q. Wang, B.L. Zhou, "Behavior of Coating on reinforcements in Some Metal Matrix Composites", *Composites Part A*, 27A, 1996, pp. 1139-45.

- [40] W. Xu, "The Influence of Chemical Composition and Heat Treatment on Microstructure and Mechanical/Tribological Properties of Cobalt-Based Triballoy Alloys", Department of Mechanical and Aerospace Engineering of Carleton University, Aug. 2005.

- [41] Y. Ning, "Effects of Sintering Process and the Coating of the Reinforcements on the Microstructure and Performance of Co-Based Superalloy Composites", Department of Mechanical and Aerospace Engineering of Carleton University, Jul. 2004.

- [42] R. Liu, W. Xu, P.C. Patnaik, M.X. Yao, and X.J. Wu, “A Newly Developed Tribaloy Alloy with Increased Ductility”, *Scripta Materialia*, Vol. 53, No. 12, Dec. 2005, pp. 1351-5.
- [43] B. Ralph, H.C. Yuen, and W. B. Lee, “The Processing of Metal Matrix Composites-An Overview”, *Journal of Materials Processing Technology*, Vol. 63, 1997, pp. 339-53.
- [44] H. M. Tawancy, N. Sridhar, N.M. Abbas, and D.S. Rickerby, “Comparative Performance of Selected Bond Coats in Advanced Thermal Barrier Coating Systems”, *Journal of Materials Science*, Vol. 35, 2000.
- [45] M. X. Yao, J. B. C. Wu, S. Yick, Y. S. Xie and R. Liu (2006), “Wear and Corrosion Resistance of a Newly Developed Laves Phase Strengthened Co-Mo-Cr-Si Alloy”, *Materials Science and Engineering A*, 2006, pp. 435-6.
- [46] “Compression Moulding Technical Information”, DuPont, USA, 2006.
- [47] R. German, “Powder Metallurgy Science”, Second Edition, Metal Powder Industries Federation Press, New Jersey, USA, 1994.
- [48] ASM Handbook Committee, “Metallography and Microstructures”, Vol. 9, ASM International, USA, 2004.

- [49] ASTM Standard Committee, “Standard Guide for Preparation of Plastics and Polymeric Specimens for Microstructural Examination”, (E2015-04), ASTM International, 2007.
- [50] “The Science Behind Materials Preparation”, Buehler Ltd., USA, 2004.
- [51] ASM Handbook Committee, “Corrosion: Fundamentals, Testing and Protection”, Vol. 13.A, ASM International, USA, 2003.
- [52] ASTM Standard Committee, “Standard Practice for Conditioning Plastics for Testing”, (D 618-05), ASTM International, USA, 2005.
- [53] ASM Handbook Committee, “Corrosion: Materials”, Vol. 13.B, ASM International, USA, 2005.
- [54] D. Xiang and K. Tao, “The Mechanical and Tribological Properties of PTFE Filled with PTFE Waste Powders”, *Journal of Applied Polymer Science*, Vol. 103, 2007, pp. 1035–41.
- [55] ASTM Standard Committee, “Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement”, (D 792 – 00), ASTM International, USA, 2001.