DEVELOPMENT OF THERMAL CONDUCTIVE PASTE FOR HEAT TRANSFER IN ELECTRONIC DEVICES

By

Muhammad Hazqeel Ejaz
Abdullah Tahir
Zukhruf Hussain

School of Chemical and Materials Engineering (SCME)
National University of Sciences and Technology (NUST)
2024

DEVELOPMENT OF THERMAL CONDUCTIVE PASTE FOR HEAT TRANSFER IN ELECTRONIC DEVICES

By

Leader - 341863 Muhammad Hazqeel Ejaz
Member 1 - 331545 Abdullah Tahir
Member 2 - 343508 Zukhruf Hussain

A THESIS

Submitted to
National University of Sciences and Technology
In partial fulfilment of the requirements for the degree of

B.E. METALLURGY AND MATERIALS ENGINEERING

School of Chemical and Materials Engineering (SCME)
National University of Sciences & Technology (NUST)
June 2024

CERTIFICATE

This is to certify that work in this thesis has been completed by **Mr. Muhammad Hazqeel Ejaz, Mr. Abdullah Tahir** and **Ms. Zukhruf Hussain** under the supervision of **Dr. Adeel Umer** and **Dr. Muhammad Siyar** at the school of Chemical and Materials Engineering (SCME), National University of Sciences and Technology, H-12, Islamabad, Pakistan.

Adeel

Advisor:

Dr. Adeel Umer
Department of Materials Engineering
School of Chemical and Materials
Engineering
National University of Sciences and
Technology

Co-Advisor

Dr. Muhammad Siyar
Department of Chemical Engineering
School of Chemical and Materials
Engineering
National University of Sciences and
Technology

Submitted Through:

HOD
Dr. Khurram Yaqoob

Department of Materials Engineering
School of Chemical and Materials
Engineering
National University of Sciences and
Technology

Manzoor 27/6/24

Principal
Dr. Umair Manzoor

Department of Materials Engineering
School of Chemical and Materials
Engineering
National University of Sciences and
Technology

ABSTRACT

A major development in thermal compound technology, polymer-based thermal pastes provide a flexible means of achieving effective heat transmission in contemporary electronics. These pastes are essential for improving the effectiveness of heat transmission between high- performance components—like CPUs and GPUs—and the cooling systems that support them. In order to minimize overheating, which can result in decreased performance, a shorter lifespan, and perhaps component failure, effective heat dissipation is essential in electronic devices. In contrast to conventional metal-based pastes, these heat pastes are safe to use around fragile electronic components because the polymer matrices make them non- conductive. To make polymer-based thermal pastes the go-to option for a variety of crucial electronics applications, this research aims to maximize thermal paste conductivity, adhesion power, durability, and simplicity of application. Thermal pastes are commonly applied in areas such as computer processors, graphics cards, power electronics, and LED lighting systems, where effective heat management is necessary to preserve longevity and peak performance. It is still very difficult to get the required amount of heat conductivity without sacrificing other crucial material characteristics or processability. These restrictions may beovercome by carefully choosing fillers and composite formulations, which gives engineers more freedom to maximize thermal solutions without sacrificing dependability. Heat conductivity may be greatly increased by the use of fillers, and the selection of the matrix material is crucial in order to strike a balance between ease of application, flexibility, and adherence. Engineers may overcome these constraints and provide more freedom to enhance thermal solutions without sacrificing dependability by carefully choosing fillers and composite formulas. The optimal performance and efficacy of the thermal paste in practical applications is determined by the fillers' and matrix's synergy, which guarantees long-term stability and excellent heat dissipation. Although there are many other types of thermal interface materials (TIMs) on the market, including liquid metal compounds and thermal pads, thermal pastes are frequently more dependable because of their exceptional ability to conform to minute surface flaws, guaranteeing optimal heat transmission and contact between surfaces. Because of their dependability,

polymer-based thermal pastes are the material of choice for many demanding and high-performance electronic applications.

DEDICATION

With deep respect,

We dedicate this endeavor to our beloved parents, respected instructors, and lab engineers, whose leadership and unwavering support encouraged us during the entire project.

ACKNOWLEDGEMENTS

We are grateful to Allah, the Most Gracious, for enabling us to do exceptionally well on our final year design project. We sincerely thank our supervisor, Dr. Adeel Umer, for his unwavering support and direction, which were crucial to the project's successful completion. We could not have accomplished this difficult task to the best of our abilities without his commitment. We also thank our co-supervisor, Dr. Muhammad Siyar, whose insightful recommendations substantially advanced our comprehension and problem-solving abilities.We also appreciate the lab engineers, attendants, and research students for helping us become familiar with the equipment and processes that are necessary for our project. We would like to sincerely thank all of the Materials Engineering department's instructors and staff for their consistent support and direction during this journey.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background

Effective heat management is essential for the optimal performance and longevity of electronic devices. As these devices become more powerful and compact, efficient heat dissipation becomes increasingly critical to prevent performance degradation, system instability, and permanent damage. Thermal conductive paste, also known as thermal grease or compound, plays a crucial role in this process by enhancing the thermal interface between heat-generating components, such as CPUs and GPUs, and heat dissipating devices like heat sinks.

The primary function of thermal conductive paste is to fill microscopic air gaps and surface imperfections between mating surfaces, which would otherwise act as thermal insulators. By doing so, it significantly improves heat transfer efficiency. The performance of these pastes depends on several key parameters, including thermal conductivity, thermal resistance, viscosity, pump-out resistance, and long-term stability. The performance of these pastes depends on several key parameters:

- *Thermal Conductivity:* The ability of the paste to efficiently conduct heat.
- *Thermal Resistance:* The measure of resistance to heat flow, where lower values indicatebetter performance.
- *Viscosity:* The thickness of the paste, affecting its application and the ability to form a thin,uniform layer.
- *Pump-out Resistance:* The ability of the paste to remain in place over time despite thermalcycling and mechanical stresses.
- *Long-term Stability:* The paste's capacity to maintain its thermal and mechanical propertiesover the lifespan of the device.

Advancements in material science have led to the development of thermal pastes with superior thermal conductivities and enhanced stability, addressing the growing demands of modern electronics. This report explores the critical role of thermal conductive paste in electronic heat management, examining its composition, key performance metrics, and the latest innovations in its formulation and application.

1.2 Problem Statement

"High and unsustainable imports of thermal paste pose a significant economic and trade imbalance challenge for Pakistan".

The importation of thermal paste from countries like the USA, Canada, Japan, and China highlights Pakistan's dependence on foreign sources for this essential component, exacerbating economic vulnerabilities and trade imbalances. Compounded by the absence of domestic manufacturing or standard-grade production, this challenge underscores the need for a comprehensive solution. Our tentative approach seeks to establish local production of standard-grade thermal paste, thereby reducing dependency on imports, promoting economic self-sufficiency, and ensuring long-term stability. Through this initiative, we aim to stimulatedomestic manufacturing, create employment opportunities, and bolster economic resilience,ultimately paving the way for a more sustainable and prosperous future for Pakistan.

1.3 Aim of Project

The aim of this project is to establish a robust domestic manufacturing capability for standard- grade thermal paste in Pakistan, reducing dependency on foreign imports, promoting economic self-sufficiency, and fostering long-term stability in the nation's thermal management sector.

1.4 Brief Introduction of Thermal Paste

Thermal paste, often referred to as thermal compound or grease, stands as an indispensableelement within the intricate architecture of electronic devices. Its role is paramount in facilitating the seamless transfer of heat between crucial components, such as CPUs (CentralProcessing Units), GPUs (Graphics Processing Units), and heat dissipation mechanisms like heat sinks. Acting as a conduit for thermal energy, thermal paste fills the minuscule gaps and imperfections that naturally occur between these components, effectively bridging the thermal interface. This meticulous sealing not only optimizes thermal conductivity but also ensures that heat is efficiently dissipated away from sensitive components. By mitigating therisk of overheating, thermal paste plays a pivotal role in preserving the performance, stability, and longevity of electronic devices, safeguarding against potential damage and maintaining consistent operational efficiency. Its significance lies not only in enhancing thermal management but also in underpinning the reliability and functionality of modern electronic systems across a myriad of applications, from consumer electronics to industrial machinery and beyond.

1.5 Applications of Thermal Paste

1.5.1. Personal Computers (PCs) and Laptops

Thermal paste is extensively used in PCs and laptops to ensure efficient heat dissipation from the CPU and GPU to the heat sink. It helps maintain optimal temperatures, preventing overheating and ensuring smooth operation even during intensive tasks like gaming or video editing.

1.5.2. Servers and Data Centres

In server rooms and data centres, where large numbers of servers are densely packed, thermal paste is crucial for managing heat generated by the processors. By enhancing thermal conductivity, it ensures reliable performance and minimizes the risk of system failures due to overheating.

1.5.3. Gaming Consoles

Gaming consoles, which often run high-performance processors, rely on thermal paste to dissipate heat efficiently. It helps prevent thermal throttling, ensuring uninterrupted gamingexperiences and prolonging the lifespan of the console hardware.

1.5.4. Mobile Devices

In smartphones and tablets, space is limited, and components are packed closely together, making efficient heat dissipation a challenge. Thermal paste is used to transfer heat away from the CPU and other internal components, preventing overheating and maintaining device performance.

1.5.5. Automotive Electronics

Modern vehicles feature sophisticated electronic systems that generate heat during operation. Thermal paste is employed in automotive electronics to dissipate heat from components such as engine control units (ECUs) and power electronics, ensuring reliability and longevity in demanding environments.

1.5.6. Industrial Machinery

In industrial settings, machinery and equipment often operate in harsh conditions with high temperatures. Thermal paste is applied to electronic components and modules to dissipate heat effectively, preventing overheating-related failures and ensuring uninterrupted operation.

1.5.7. Aerospace and Defence Systems

Aerospace and defence systems require reliable thermal management to operate efficientlyin extreme environments. Thermal paste plays a vital role in dissipating heat from critical components such as avionics systems and radar equipment, ensuring optimal performanceand mission success.

1.5.8. Medical Devices

In medical equipment such as MRI machines, ultrasound devices, and patient monitoring systems, thermal management is crucial for maintaining device reliability and patient safety.Thermal paste helps dissipate heat from sensitive electronic components, ensuring consistent performance in healthcare settings.

1.6 Research Objectives

Objective 1: To identify the best combination of matrix and fillers for the development ofhighly effective thermal paste formulations.

This objective focuses on researching and selecting the optimal materials that make up thermal paste. The matrix (base material) and fillers (conductive particles) are crucial in determining the thermal conductivity and overall performance of the paste. By identifying the best combination, the goal is to develop a thermal paste that maximizes heat transfer efficiency and stability.

Objective 2: To comprehensively characterize the properties and characteristics of the thermal paste fabricated.
This objective involves a thorough analysis of the thermal paste produced, assessing its thermal conductivity, thermal resistance, viscosity, pump-out resistance, and long-term stability. Comprehensive characterization ensures that the paste meets the required performance standards and can be reliably used in electronic applications.

Objective 3: To optimize the formulation of thermal paste with the most suitable thermal and electrical properties.
This objective aims to refine and enhance the formulation of the thermal paste to achieve thebest possible thermal and electrical performance. Optimization involves adjusting the proportions and types of materials used in the paste to ensure it delivers superior heat dissipation while maintaining electrical insulation properties where necessary.

1.7 Working Principle

Thermal pastes facilitate heat transfer between the heat-generating component, such as a CPU or GPU, and the heatsink through a process involving the scattering of vibrating phonons. Phonons are quantized lattice vibrations in solids that carry thermal energy. When the thermal paste fills the microscopic gaps between the mating surfaces, it forms a continuous medium through which phonons can propagate. As heat flows from the component to the thermal paste, phonons travel through the paste via lattice vibrations. However, due to the presence of impurities, grain boundaries, and other defects within the paste, phonons
experience scattering events as they move through the material. These scattering events

cause phonons to change direction and velocity, effectively diffusing the thermal energy. By encouraging the redistribution of thermal energy throughout the thermal paste and simplifying its transfer to the heatsink, this scattering process improves heat transfer. Thermal pastes, therefore, are essential for maximizing heat dissipation in electronic devicesbecause they increase thermal conductivity and boost overall cooling efficiency by taking advantage of the dispersion of vibrating phonons.

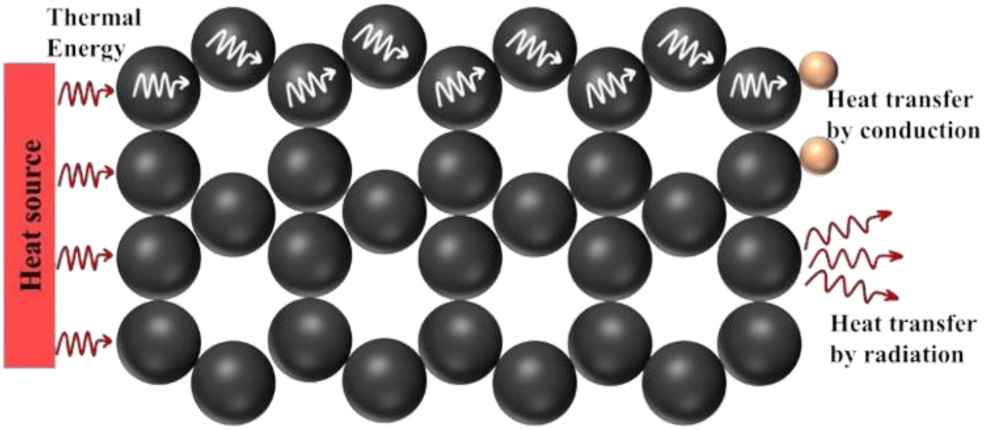

Figure 1 Heat transfer Mechanism in Thermal Paste

CHAPTER 2

LITERATURE REVIEW

2.1 Graphite Nanoplatelet-based epoxy composites as adhesives and pads for thermal interface applications

The goal of this work is to improve the performance of thermal interface materials (TIMs) by developing and accessing composites composed of rubbery epoxy (RE) resins and graphite nanoplatelets (GNPs). Using a 3-roll milling technique, two sizes of GNPs—15 μm (GNP-15) and 5 μm (GNP-5)—were added to RE. Scanning electron microscopy (SEM) verified that theoutcome was a uniform dispersion. Less platelet alignment was shown by X-ray diffraction texture studies at lower GNP loadings, indicating effective dispersion without considerable alignment that may have an impact on mechanical and thermal capabilities[1].

The GNP/RE composites shown notable gains in thermal conductivity: 20 weight percent GNP-15/RE reached 3.29 W/m-K, while 35 weight percent GNP-5/RE obtained 2.36 W/m-K.The thermal conductivity of pure RE was measured at 0.17 W/m-K. These improvements show how GNPs can help TIMs dissipate heat more effectively[2]. The composites also demonstrated good electrical conductivity and compliance, and their compressive properties were on par with those of commercial TIMs made of silicone and boron nitride (BN).

Because of the strong adhesive properties of RE, the interfacial thermal transport of GNP/RE composites performed better than that of GNP/silicone composites. This resulted in a decreased thermal contact resistance in the 20 weight percent GNP-15/RE thermal pad, particularly when pressure was raised. In general, the GNP/RE composites exhibit potential as efficient adhesives and pads for thermal interfaces, providing better thermal control and possible financial advantages over traditional TIMs.

2.1.1 Synthesis

The Hummers technique was used to treat graphite powder and flakes, and thermal reduction was then performed to create GNPs and FLGs. These were mixed with solvent mixture and sonicated into rubbery epoxy at a 4 weight percent (2.1 volume percent) concentration, together with commercial MWCNTs and GNPs and internally generated FLG and GNPs. Usingelectron microscopy, the morphology of the fillers and the resultant composites was examined. These composite TIMs were assessed using the ASTM D5470 technique to determine their TCR before being employed as adhesive coatings. The results showed that asMWCNT loading increased from 1 to 8 wt%, the TCR of MWCNT-epoxy composites increased as well. To be more precise, at a bond line thickness of 15 μm, a 1 weight percent MWCNT/rubbery epoxy composite showed a TCR of 1.05 × 10−4 m^2K/W, which was much greater than that[3].

2.1.2 Thermal contact resistance of various carbon nanomaterial-based

Since they improve the thermal contact between the chip and the heat-sink, thermal interfacematerials (TIMs) are crucial to the efficient dissipation of heat from microchips in electronic packaging[4]. Filler-based polymer composite TIMs are essential to this procedure since they are frequently utilized as pastes or adhesives. Because of their high heat conductivity, carbon nanomaterials—such as carbon nanotubes, graphite nanoplatelets (GNPs), few-layered graphene nanosheets (FLG), and carbon nanofibers—are being extensively studied for the development of thermoelectric materials (TIM). The thermal contact resistance (TCR) of epoxy composites containing GNPs, FLG, or MWCNTs is compared in this study under comparable experimental conditions.

The in-house GNP-based composite was found to have the lowest TCR of 1.9 × 10−5 m^2K/W at a bond line thickness of 18 μm, which was half that of the similar FLG-based composite. The reduced TCR is ascribed to the in-house synthesized GNP's less faulty structure in comparison to FLG. As a result, epoxy composites using internally generated GNPs outperform those using commercial GNPs, MWCNTs, or FLGs in terms of heat dissipation.

2.2 Preparation and properties of Epoxy/BN highly thermal conductive composites reinforced with SiC whisker

2.2.1 SiC Whiskers as Fillers

This work describes a simple technique for adding silicon carbon whiskers (SiCw) and micro- boron nitride (BN) treated with particular silcane coupling agents to improve the mechanical and thermal conductivity of epoxy composites. 3-aminopropyltriethoxysilane (KH550) was used to treat the BN particles, whereas 3-glycidyloxypropyltrimethoxysilane (KH560) was used to treat the SiCw particles.

2.2.2 Epoxy Matrix

The main emphasis of the study was how epoxy/BN composites' flexural strength and thermal conductivity were affected by BN particle surface modification[5]. The flexural strength of the composites was significantly increased by 13.8–17.8% upon the addition of BN grafted with KH550 and about 3% SiCw particles grafted with KH560. Along with the good dielectric characteristics, there was a little improvement in heat conductivity.

2.2.3 Mechanical Strength

The addition of these fillers resulted in a significant increase in the storage modulus of the composites as determined by dynamic mechanical analysis, despite a little fall in the glass transition temperature[6]. Overall, this technology is useful for enhancing the performance of materials used in a variety of applications because it provides a workable way to simultaneously improve the mechanical and thermal conductivity qualities of epoxy composites.

2.2.4 Silicon Carbon Whiskers (SiCw) Treatment

To improve their compatibility and bonding with the epoxy matrix, 3-glycidyloxypropyltrimethoxysilane (KH560) was applied to silicon carbon whiskers (SiCw)[7]. The following actions were part of the treatment process:

1. Making the Silane Solution: To make a silane solution, KH560 was dissolved in an appropriate solvent, such as ethanol or water.
2. Condensation and Hydrolysis: To create silanol groups, the KH560 silane solution

underwent condensation and hydrolysis processes. Bonding is facilitated by the silanol groups' great attraction for the hydroxyl groups on the SiCw surface.

3. Surface Treatment of SiCw Particles: After immersing the SiCw particles in the silane solution, the silanol groups were able to interact with the whisker surface. The SiCw particles were coated with functional epoxy groups as a result of this reaction, which created a covalent linkbetween the silane coupling agent and the particles.
4. Drying and Curing: To get rid of any remaining solvent, the SiCw particles were dried after the procedure. In order to guarantee that the silane coupling agent was firmly attached to the SiCw surface, the particles were then cured at a high temperature.

Using KH560 to modify the surface of SiCw offered the following advantages:

1. Better Dispersion: The epoxy groups on the SiCw particles with surface modifications improved their dispersion in the epoxy resin, avoiding aggregation and guaranteeing a uniform distribution all across the composite.
2. Enhanced Interfacial Bonding: Better stress transmission and enhanced mechanical characteristics resulted from the functional groups on the modified SiCw particles' improved interaction and bonding with the epoxy matrix.
3. Improved Thermal Conductivity: By creating a more effective thermal route, the improved dispersion and stronger interfacial bonding increased the composite's thermal conductivity.

2.3 A Review of the Performance and Characterization of Conventional and Promising Thermal Interface Materials for Electronic Package Applications

Thermal interface materials (TIMs) are essential for increasing the efficiency of heat transmission because they lower the thermal resistance between solid surfaces, including heat sinks and circuit boards[8]. An overview of TIMs' significance in electrical devices and how they improve heat dissipation is given in this section.

2.3.1 Conventional TIMs

Greases, the most commonly used conventional TIMs, are discussed here.. Grease is widely used, but it has drawbacks. For example, its high viscosity makes it difficult to apply and remove, which can lead to dependability problems including pump-out, phase separation, and dry-out. Grease typically has a heat resistance range of 0.1–1 cm^3°C/W.

2.3.2 Advanced TIMs

The advanced TIMs, such as those that incorporate nano-metal particles and carbon nanotubes (CNTs), are the subject of this section. In comparison to traditional greases, these TIMs exhibit lower thermal resistances (0.01-0.19 cm^3°C/W). However, using CNT-based TIMs presents certain difficulties, like uneven heat dispersion. For high-temperature applications in electronic packaging systems, more study is necessary, particularly with reference to carbon nanotubes (CNTs). Nano-metal particle TIMs appear promising.

2.3.3 Thermal Performance and Measurement Techniques

This section of the paper addresses the methods for measuring the efficacy of both traditional and advanced TIMs, as well as their thermal performance. It highlights areas in need of moreinvestigation to improve thermal management in electronic devices and offers insights into the advantages and drawbacks of various TIMs.

CHAPTER 3

MATERIAL SELECTION

Choosing the right ingredients for thermal pastes is a critical step in developing high-performance thermal interface materials (TIMs). Among the various options, polymers standout due to their unique and versatile properties, making them an exceptional choice for thermal paste formulations.

Polymers offer an impressive range of attributes that make them suitable for TIM applications:

Enhanced Thermal Stability: Polymers can withstand high temperatures without degrading, ensuring consistent performance over time.

Mechanical Flexibility: Their inherent flexibility allows polymers to conform to irregular surfaces, filling microscopic gaps and ensuring better contact between components.

Ease of Manufacturing: Polymers are relatively easy to process and can be manufactured intovarious forms, simplifying the production of thermal pastes.

Compatibility with Fillers: Polymers can be effectively combined with conductive fillers such as metal particles or carbon nanotubes to significantly boost thermal conductivity.

Electrical Insulation: One of the standout benefits of polymers is their natural insulating properties, which help prevent electrical conductivity, thereby reducing the risk of short circuits and other electrical issues in thermal management applications.

These characteristics not only make polymers a practical choice but also innovative solution for enhancing the performance of thermal pastes. Their ability to improve thermal stability, mechanical flexibility, and ease of manufacturing, combined with their compatibility with various fillers and excellent insulating properties, positions polymers as the ideal base for developing advanced TIMs.

3.1 Material proposed and their properties

Epoxy is a suitable option for the matrix because of its high adhesion, chemical resistance, and simplicity of processing. SiC whiskers are used to improve the mechanical and thermal properties of composites because of their remarkable strength, stiffness, and thermal conductivity. BeO was chosen because of its excellent thermal conductivity, which makes heat transmission more efficient. The strong bonding matrix that epoxy provides to the BeO and SiC whiskers enhance the mechanical strength and thermal conductivity of the composite. They are used extensively in coatings and adhesives because to their strong bonding capabilities; in high-performance ceramics, SiC whiskers are used because of their exceptional strength; and in electronic components, BeO has excellent thermal conductivity.

3.2 Expected Results

3.2.1 Increase in Thermal Conductivity

Our efforts are poised to yield thermal pastes with a substantial increase in thermal conductivity. This advancement is anticipated to be driven by the integration of high-performance fillers such as silicon carbide (SiC) whiskers and beryllium oxide (BeO) particles. By leveraging these advanced fillers, we expect to significantly enhance the efficiency of heattransfer, which is paramount for optimizing thermal management in diverse electrical systems and devices.

3.2.2 Increase in Adhesive Strength

Projections suggest that the thermal pastes under development will showcase enhanced adhesive strength, resulting in more robust surface bonding. This improvement is expected to bolster the reliability and overall dependability of thermal interfaces across a spectrum of operational scenarios, ensuring sustained performance under various environmental conditions.

3.2.3 Improvement in Mechanical Properties

We anticipate notable improvements in the mechanical properties of the thermal pastes, with a focus on increasing strength and durability. By fortifying the structural integrity of the paste, we aim to enhance its resilience against mechanical stresses, thereby extending its longevityand ensuring prolonged effectiveness in real-world applications.

3.2.4 Optimization of Dispersion

A key objective of this study is to optimize the dispersion of fillers within the epoxy matrix. Through meticulous control and refinement of filler distribution, we aim to achieve a more uniform dispersion throughout the paste. This optimization strategy is poised to elevate the overall efficacy of the paste in facilitating heat transfer and enhancing thermal conductivity.

3.2.5 Decreased Electrical Conductivity

Our endeavours are expected to yield thermal pastes with diminished electrical conductivity. By mitigating the risk of electrical shorts in electronic systems, this advancement holds significant implications for enhancing the reliability and safety of electronic devices in various operational environments.

3.2.6 Increase in Thermal Stability

Lastly, we anticipate a substantial enhancement in the thermal stability of the developed thermal pastes. By enabling the pastes to maintain their thermal properties across a broad range of operating temperatures, this improvement is poised to elevate the overall performance and reliability of thermal management systems in demanding electronic applications.

By pursuing these anticipated improvements, our aim is to develop thermal pastes that not only excel in thermal conductivity but also offer enhanced mechanical properties, augmented adhesive strength, refined filler dispersion, reduced electrical conductivity, and heightened thermal stability. These advancements are pivotal for advancing the efficacy and reliability of thermal management solutions in modern electronic devices and systems.

CHAPTER 4

EXPERIMENTAL DESIGN

4.1 Uniform Mixing through Hotplate Method of BeO and SiC Whiskers in Epoxy Matrix

A hotplate approach was used to achieve uniform dispersion of silicon carbide (SiC) and beryllium oxide (BeO) whiskers within the epoxy matrix through a homogenous mixing procedure. BeO and SiC whiskers were first measured in volumes that were predetermined to correspond to filler concentrations of 1%, 2%, and 5%. The epoxy resin was then placed on ahotplate that had been heated to an exact, regulated temperature, and these carefully measured fillers were gradually added to the resin. To guarantee effective mixing and to make it easier for the fillers to properly integrate into the epoxy matrix, this regulated heating wasessential.

Throughout the mixing procedure, stirring was done continuously to help ensure that the fillers were distributed evenly and to stop clumping or agglomeration inside the epoxy matrix. To guarantee that the fillers were evenly distributed and to maintain a consistent consistency, the temperature, time, and rate of stirring were closely observed and changed as needed. Achieving homogeneity in the final thermal paste's mechanical and thermal conductivity properties required careful attention to the mixing conditions.

The hotplate method's precise temperature control was crucial in lowering the epoxy resin'sviscosity, enabling the SiC and BeO whiskers to be dispersed uniformly without jeopardizingthe matrix's integrity. Additionally, by continuously stirring, the epoxy resin was thoroughlycoated on the whiskers, improving the interfacial bonding between the fillers and the matrix.To maximize the thermal paste's mechanical durability and thermal conductivity, a strong interfacial connection is essential.

A homogenous dispersion of SiC and BeO whiskers within the epoxy matrix was attained by strictly regulating the temperature, speed of stirring, and rate of filler addition throughout the mixing process. This homogeneity is essential for the paste's mechanical and thermal performance as well as for ensuring that the finished product behaves consistently and dependably under operating conditions. With its evenly distributed fillers, the resulting thermal paste should exhibit better adhesion, increased durability, and increased thermal conductivity, making it appropriate for high-performance electronic applications.

4.2 Samples with different compostions

In order to create a comparison, a set of thermal paste samples with pure epoxy resin and samples incorporating BeO and SiC whiskers in varied concentrations (1% to 5%) were made To guarantee precision in the filler content, precise measurements of the specified amounts of BeO and SiC whiskers were made. The epoxy resin was then mixed thoroughly with the filler mixes using the previously established hotplate procedure. In order to assure a uniformdistribution of the whiskers inside the epoxy matrix and to allow efficient mixing, this procedure included heating the resin to a specified temperature.

To ensure traceability, each mixture was carefully labeled and preserved throughout the experiment. To preserve its integrity, every sample was meticulously labeled with details about its composition, such as the proportion of BeO and SiC whiskers, and kept in a controlled environment. The meticulous documentation procedure made it possible to accurately trackand compare the various samples.

Using the same hotplate mixing method, control samples made entirely of pure epoxy resin were created in addition to the filled epoxy samples. To ensure that any variations in the mechanical and thermal properties of the samples could be attributed to the presence and concentration of the fillers rather than variations in the mixing process, consistency in the preparation method was essential for producing comparable data.

Both the filled and unfilled samples underwent a thorough study in order to determine the effect of filler content on the mechanical and thermal properties of the thermal paste. Evaluations of adhesion strength, durability, thermal conductivity, and other pertinent mechanical parameters were included in this analysis. The impact of the fillers on the overallperformance of the thermal paste may be thoroughly examined by contrasting the performance of the pure epoxy resin samples with those having varying quantities of BeO and SiC whiskers.

The studies' outcomes shed important light on how changing the filler content influences thethermal paste's mechanical characteristics and thermal conductivity. With the help of this knowledge, polymer-based thermal paste formulations can be optimized to produce the right combination of performance qualities, making them appropriate for a variety of high-performance electronic applications.

4.3 Mixing Epoxy with Hardener in Ratio of 7.5:2.5

To guarantee appropriate curing and efficient crosslinking of the polymer matrix, the epoxy resin and hardener were precisely mixed at a ratio of 7.5:2.5 prior to the addition of the fillers.

Using calibrated equipment, precise measurements of the hardener and epoxy resin were achieved, ensuring uniformity and reproducibility throughout all samples. The integrity and dependability of the experimental outcomes depended heavily on this methodical methodology.

The epoxy resin and hardener were completely mixed using mechanical agitation to ensure that the components were distributed uniformly and to facilitate the crosslinking process. Inaddition to hastening the chemical reactions required for curing, this vigorous mixing also assisted in removing any possible air bubbles or irregularities from the mixture. For the cured epoxy composites to have the best possible mechanical strength, thermal stability, and adhesive qualities, a homogeneous mixture had to be achieved.

After the hardener and epoxy resin had been well combined, the appropriate amounts of BeOand SiC whiskers were added little by little to the mixture. In order to enable the fillers to disperse evenly, the mixture was heated to a certain temperature using the previously devised hotplate method. The whiskers were evenly dispersed throughout the epoxy matrix thanks to constant stirring during this phase, which also prevented agglomeration and guaranteed consistency in the finished product.

The experiment attempted to create epoxy composites with ideal characteristics by precisely controlling the mixing ratios and process parameters. For the fillers to be added and dispersed in a methodical manner and to achieve the desired increases in mechanical strength, durability, and thermal conductivity, the epoxy resin and hardener had to be carefully prepared.

Then, a thorough testing program was implemented to assess the mechanical and thermal properties of these painstakingly manufactured samples, both with and without fillers. These studies yielded important information about how the addition of BeO and SiC whiskers at different concentrations affected the epoxy composites' overall performance. The goal of this thorough analysis was to determine the ideal filler concentration and mixing parameters needed to create high-performance polymer-based thermal pastes appropriate for cutting- edge electronic applications.

4.4 SEM, XRD, and FTIR Characterization of Fillers

X-ray diffraction (XRD), scanning electron microscopy (SEM), and Fourier transform infrared spectroscopy (FTIR) were used to thoroughly evaluate the whiskers of silicon carbide (SiC) and beryllium oxide (BeO) prior to their addition to the epoxy matrix. The existence of crystalline phases was detected using XRD, which gave crucial details regarding the fillers' structural properties. The size, shape, and distribution of the fillers were thoroughly examined using SEM analysis, which provided comprehensive insights into their morphology and confirmed that they complied with the requirements for integration into the epoxy matrix. The functional groups contained in the fillers were identified and the chemical composition was clarified using FTIR spectroscopy. Understanding the potential chemical interactions between the fillers and the epoxy matrix was made possible by this analysis, which helped shape the formulation process and maximize the thermal paste's performance and compatibility.

The applicability and quality of the SiC and BeO whiskers for the fabrication of thermal pastewere guaranteed by these characterization techniques. A thorough understanding of the fillers' characteristics was made possible by the data from XRD, SEM, and FTIR, which allowed for exact formulation changes to improve filler-matrix interactions. Ensuring that the fillers would properly contribute to the final thermal paste's mechanical strength, thermal conductivity, and overall performance was made possible by this exhaustive evaluation process. The formulation procedure intended to create a thermal paste that satisfies the demanding requirements of contemporary electronic applications, guaranteeing dependability and efficiency in heat dissipation, by incorporating these premium fillers into the epoxy matrix.

4.5 Mold Preparation with Plastic Bottle Cap to Attain Uniform and Specific Dimensions for Thermal Conductivity Test

To guarantee that every sample had the same, predefined dimensions for the thermal conductivity test, plastic bottle tops were recycled and used as molds. The inner diameter and depth of every plastic cap were carefully measured to ensure accurate and consistent sample sizes and to attain consistency among all specimens. In order to produce comparable and trustworthy test findings, this procedure was essential.

The plastic caps were meticulously cleaned to get rid of any contaminants that might have an impact on the quality of the cured samples before the molding process started. The interior sides of the caps were coated with a release agent to make it easier to remove the cured samples from the molds. By generating a non-stick surface, this procedure guaranteed that the samples could be removed without causing any harm to the epoxy composites and prevented them from sticking to the mold.

Each prepared mold was then filled with meticulously mixed thermal paste compositions, which included the exact amounts of epoxy resin, hardener, and fillers. The thermal paste was carefully poured into the molds to ensure that there were no voids or air bubbles that could affect the samples' integrity. To ensure consistency across all samples, any extra material was meticulously scraped off to leave a smooth and level surface.

The molds were placed in a quiet area to allow the epoxy composites to cure completely afterthey were filled and polished on both sides. This curing interval was required for the epoxy resin to undergo the crosslinking process, harden the material, and impart the proper mechanical and thermal attributes. The temperature and duration of the curing process were carefully controlled to provide consistent results.

For the purpose of the thermal conductivity tests, uniform samples were created by utilizingplastic bottle caps as molds and carefully preparing and curing the samples. The precise assessment of the thermal performance of the various thermal paste compositions was madepossible by these samples, which also made it possible to compare in-depth the impacts of different filler contents on the mechanical and thermal properties of the epoxy composites.

Figure 2 Plastic molds for sample preparation

4.6 Preparing Samples for Adhesion Test with Thermal Paste of Each Composition Separately by Using Aluminum Strips

Aluminum strips with layers of thermal paste in various compositions were utilized to makesamples for adhesion testing. By keeping a bonded region on the aluminum strips with exactmeasurements of 5 mm in length and 10 mm in width, consistency in testing parameters wasguaranteed. The adhesive strength of all samples may be measured with accuracy andcomparability because to this uniform bonding area.

The thermal paste was applied equally to each pair of aluminum strips, guaranteeing a homogeneous layer that would yield reliable adhesion outcomes. To ensure that the paste was evenly dispersed across the bonded zone, a controlled amount of paste was applied to one strip during the coating process, and the second strip was pressed onto it. All of the strips were subjected to equal pressure in order to ensure a strong adhesive bond and remove anyair pockets that might compromise it.

The completed samples were left undisturbed to allow the thermal paste to completely dry after applying pressure. This curing time was critical because it enabled the crosslinking of the epoxy matrix in the thermal paste, hardening the mixture and creating a firm connection between the aluminum strips. In order to guarantee that every sample was cured under the same circumstances and to exclude any potential influences on the adhesion test results, the curing parameters, including temperature and duration, were meticulously regulated.

Following complete curing, adhesion testing was performed on the samples. This requires measuring the force needed to break the adhesive bond and using a controlled force to separate the glued aluminum strips. This test was carried out under controlled conditions, and important data regarding the adhesive strength of each thermal paste composition was acquired. Strong adhesion is essential for preserving efficient thermal interfaces between components in real-world applications, and these findings shed light on the thermal paste's appropriateness for such situations.

The precise evaluation of the adhesive qualities of the heat pastes was made possible by the meticulous methodical preparation and testing of the samples. In order to satisfy the requirements of high-performance electronic applications, the most efficient thermal paste compositions would be chosen based on the test findings, which would balance heat conductivity with strong adhesive characteristics.

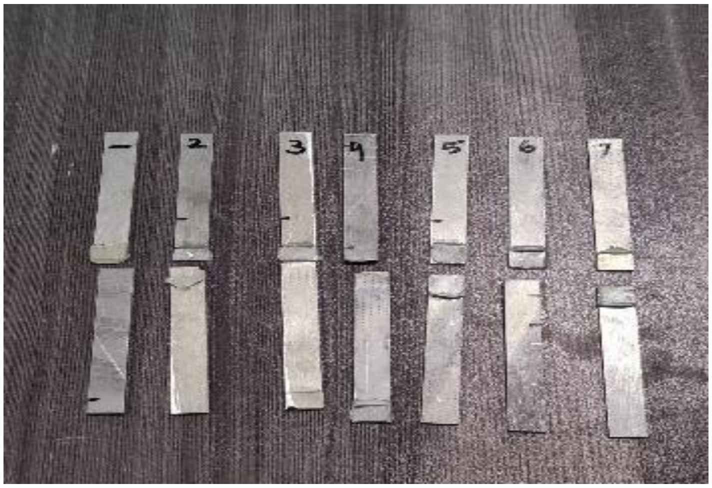

Figure 3 Sample preparation for adhesion test

4.6.1 Comprehensive Evaluation of Cured Epoxy Composites

Following the curing process, a thorough examination of the mechanical and thermal properties of the cured epoxy composites was carried out. Adhesion testing, thermal conductivity assessment, and microstructure characterization using techniques like scanningelectron microscopy (SEM) and X-ray diffraction (XRD) were among the experiments carried out.

DRX II PS was used to measure the samples' thermal conductivity in order to ascertain how the filler content affected the samples' capacity for heat transmission. This investigation offered insightful information about how well various filler compositions work to improve heat dissipation and thermal conductivity within the epoxy matrix.

The strength of the binding between the substrates and thermal paste was assessed using adhesion tests. Important details on the thermal paste's adhesive qualities and capacity to sustain functional thermal surfaces in practical settings were revealed by this test.

Using XRD and SEM methods, the microstructure of the dried epoxy composites was investigated. These investigations made it possible to characterize the filler distribution, size, and general shape inside the epoxy matrix in great detail. Researchers were able to comprehend the effects of filler distribution and content on the mechanical and thermal properties of the thermal paste by examining the microstructure.

All things considered, this exhaustive investigation yielded insightful information that may be applied to strengthen thermal paste's composition and increase its appropriateness for thermal management applications. Thermal pastes with enhanced adhesive strength, thermal conductivity, and overall performance can be created by optimizing the filler content, distribution, and formulation, satisfying the stringent needs of contemporary electronic systems and gadgets.

CHAPTER 5

RESULTS AND ANALYSIS

5.1 Scanning Electron Microscopy (SEM)

In material science and engineering, scanning electron microscopy (SEM) is a vital instrument that provides unparalleled insights into the microstructure and morphology of materials. SEM examination is essential for comprehending the distribution, size, and arrangement of the fillers inside the epoxy matrix for creating thermal paste. To maximize the thermal paste's overall performance and thermal conductivity, this information is essential.

SEM is required because of the complex fillers in the epoxy matrix, like beryllium oxide (BeO) and silicon carbide (SiC) whiskers. SEM, in contrast to conventional light microscopy, uses a concentrated electron beam to scan the sample's surface and produce images with far betterresolution. This makes it possible for researchers to see the fillers' nanoscale characteristicsand evaluate how they are distributed and aligned within the matrix.

SEM also makes it possible to analyze the fillers, figuring out things like size distribution, aspect ratio, and interparticle spacing. Understanding how the fillers interact with the epoxy matrix and how they affect the finished product's thermal conductivity is made possible withthe help of these insightful observations.

Following is the description of the SEM results of SiC Whiskers and BeO with their deep Analysis:

5.1.1 SiC Whiskers

The silicon carbide (SiC) whiskers' SEM examination provided important new information on their morphology and size. The findings showed that the SiC whiskers had a consistent thickness range, usually with a diameter of 250–300 nanometers. This constant thickness is important since it guarantees that the material's thermal conductivity is the same throughout. Furthermore, the SiC whiskers' elongated structure could be clearly seen in the SEM pictures. Since it directly affects the effectiveness of heat transfer across interfaces, knowledge of the SiC whiskers.

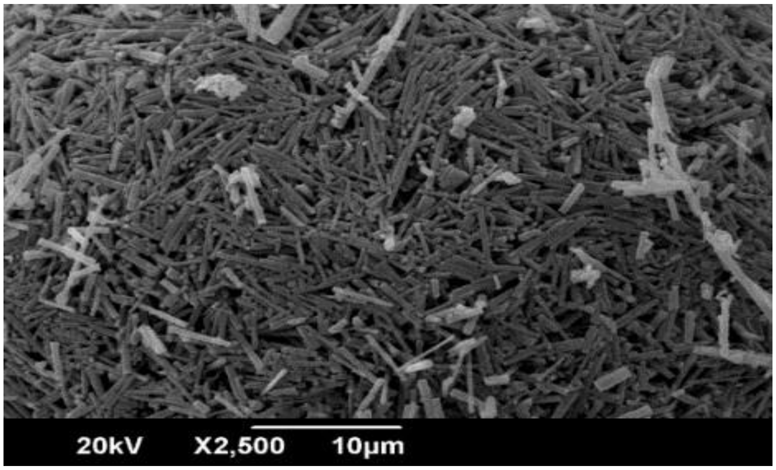

Figure 4 SEM image 1 of SiC whiskers

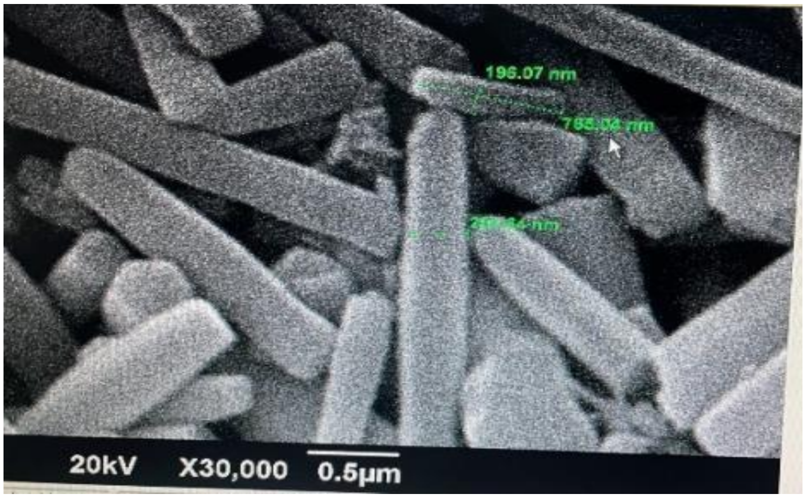

Figure 5 SEM image 2 of SiC whiskers

5.1.2 BeO

The SEM examination of the beryllium oxide (BeO)[4] particles revealed important features related to their use in the creation of the thermal paste. The findings demonstrated that the BeO particles had a regular distribution of particle sizes, usually falling within the range of 100 to 150 nanometers. This consistency in particle size is important since it guarantees that the material's thermal conductivity is the same throughout. The morphology of the BeO particles was shown in depth by the SEM pictures, which also highlighted their spherical or irregular forms. Since it directly affects heat dissipation efficiency, knowing the size and distribution of the BeO particles is essential for optimizing the thermal properties of the thermal paste. These SEM results provide important information for optimizing the composition of the thermal paste to improve its overall performance and thermal conductivity.

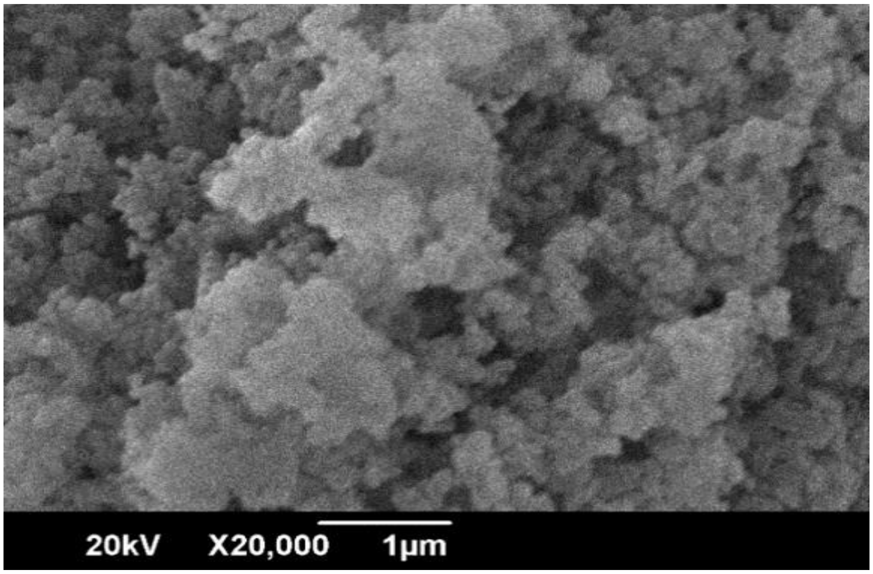

Figure 6 SEM image of Beryllium Oxide (BeO)

5.2 X-Ray Diffraction (XRD)

An essential method in material science for examining the crystalline structure and phase composition of solid samples is X-ray diffraction (XRD) examination. When it comes to thermal paste production, X-ray diffraction (XRD)[8] is an essential instrument for describing the fillers that are mixed into the matrix, like beryllium oxide (BeO) particles and silicon carbide (SiC) whiskers. Through the application of X-rays to the fillers and the subsequent diffraction patterns, XRD allows researchers to determine which crystalline phases are present, evaluate their purity, and examine their crystallographic properties. Understanding the fillers' structural characteristics and any effects on the thermal conductivity and overall functionality of the thermal paste requires knowledge of this kind. Consequently, XRD analysis is essential to the thorough characterization and optimization of thermal paste formulationsfor various applications.

5.2.1 XRD of BeO

The crystalline structure and phase composition of the beryllium oxide (BeO) particles were elucidated using X-ray diffraction (XRD) research. The presence of the intended crystalline phase was confirmed by the diffraction patterns, which showed distinctive peaks corresponding to the beryllium oxide crystallographic planes. Additionally, the absence of other peaks demonstrated the purity of the BeO particles, indicating no contaminants or secondary phases that could compromise their thermal stability.

Important structural information was obtained by determining the crystal orientation, crystallite size, and lattice parameters through the examination of peak intensities and positions. Overall, the XRD results confirmed the crystalline nature and purity of the BeO particles, essential for their effective integration into thermal paste formulations, contributing to optimized thermal conductivity and performance.

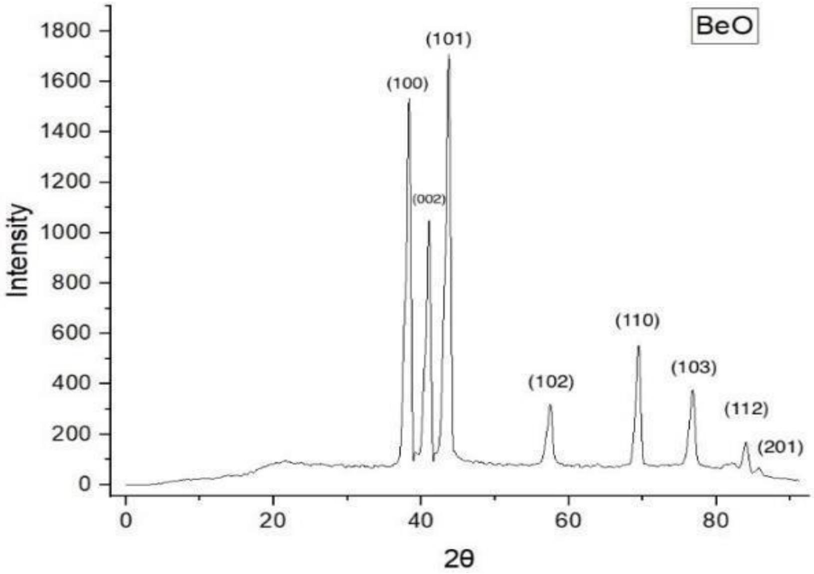

Figure 7 XRD results of BeO powder

5.2.2 XRD for SiC

The crystalline structure and phase composition of the silicon carbide (SiC) whiskers were elucidated using X-ray diffraction (XRD) research. The presence of the intended crystalline phase was confirmed by the diffraction patterns, which showed distinctive peaks corresponding to the silicon carbide crystallographic planes. Furthermore, the lack of other peaks demonstrated the purity of the SiC whiskers that is, the absence of contaminants or secondary phases that would affect their thermal stability. Important structural informationwas obtained by determining the crystal orientation, crystallite size, and lattice parameters through the examination of peak intensities and positions. Overall, the XRD results confirmed the crystalline nature and purity of the SiC whiskers, essential for their effective integration into thermal paste formulations, contributing to optimized thermal conductivity and performance.

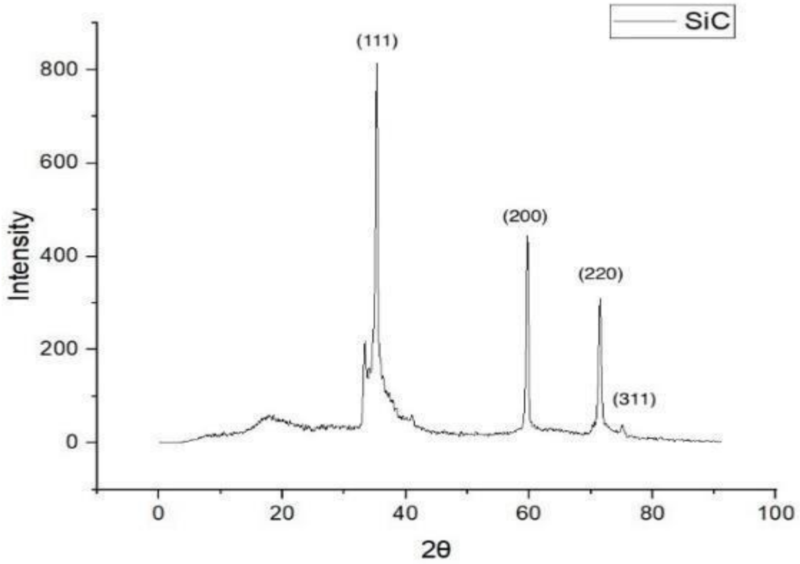

Figure 8 XRD results of SiC whiskers

5.3 Fourier Transform Infrared Spectroscopy(FTIR)

In material science and polymer chemistry, Fourier Transform Infrared Spectroscopy (FTIR) is a basic analytical technique that is frequently used to clarify the chemical structure and composition of materials. Understanding the molecular structure and functional groups of the epoxy matrix is crucial for our effort on thermal paste fabrication, and this is best achieved by FTIR analysis. FTIR is a useful technique for gaining insights into the chemical bonds that exist inside the matrix. It works by exposing the epoxy resin to infrared radiation and measuring the absorption or transmission of the resulting spectrum. This makes it possible for researchers to pinpoint important functional groups that are essential to the characteristics and functionality of the matrix, like hydroxyl (-OH), methyl (-CH3), and epoxy (-O-). Furthermore, FTIR analysis offers qualitative and quantitative information about the degree of curing or crosslinking within the epoxy matrix, influencing its mechanical strength, thermal stability, and adhesive properties. Thus, the introductory FTIR analysis sets the stage for a comprehensiveunderstanding of the epoxy matrix's chemical composition and structure, laying the foundation for subsequent optimization and enhancement of the thermal paste formulation.

5.3.1 Results

The epoxy matrix's FTIR research revealed important details about its molecular structure and chemical makeup. The resulting spectrum showed several peaks that corresponded to different functional groups found in the epoxy resin, such as hydroxyl (-OH), methyl (-CH3), and epoxy (-O-) groups. The degree of crosslinking or curing inside the epoxy matrix was also provided by the FTIR spectrum, which is important information for assessing the material's mechanical qualities and thermal stability. Through analysis of the FTIR data, the chemical properties of the epoxy matrix were better understood, which made it easier to optimize theformulation of the thermal paste for improved performance in thermal management applications.

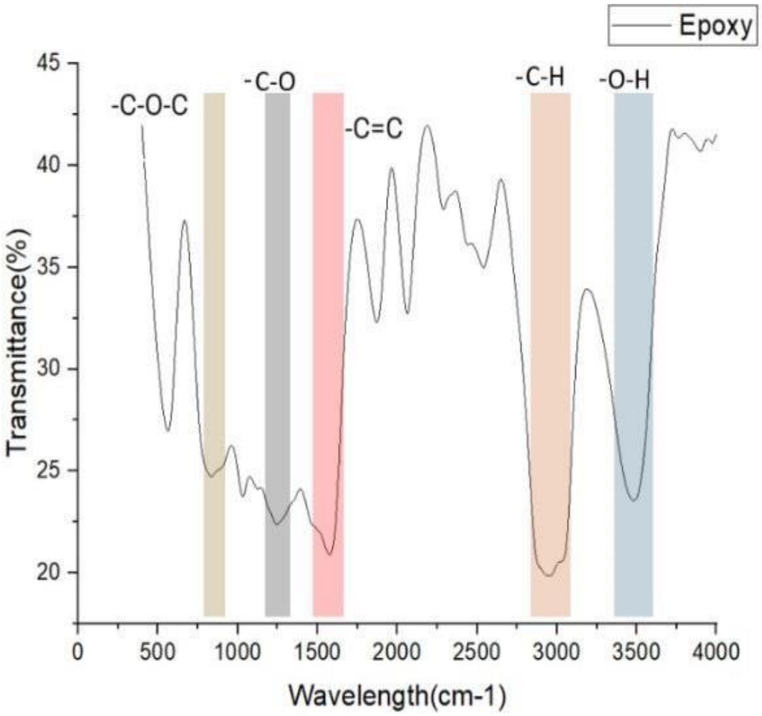

Figure 9 FTIR of Epoxy

CHAPTER 6

RESULTS AND ANALYSIS OF FABRICATED THERMAL PASTES

6.1 Thermal Conductivity Test

To evaluate the critical property of thermal conductivity in standard-grade thermal paste, weconducted tests on eleven distinct samples using the equipment DRX 2 PS. Sample 1 comprised simple epoxy without reinforcement[7], while Samples 2, 3, 4, 5 and 6 featured 1%, 5%, 20%, 40% and 60% weight of BeO, respectively. Similarly, Samples 7, 8, 9, 10 and 11 incorporated 1%, 5%, 20%, 40% and 60% weight of SiC whiskers.

Given the temperature variations in electronic devices (40-80 degrees Celsius), our tests covered this range. This systematic approach enables us to discern the thermal conductivity variations across different samples and temperatures. By increasing the amount of fillers an increase in the values of thermal conductivity was observed.

6.1.1 At Room Temperature

At room temperature, thermal conductivity of Sample 1 (epoxy) was 0.2 W/m-k and by increasing the amount of fillers the values of thermal conductivity were also increased. Thermal conductivities of sample 2 (1 Wt% BeO) and sample 7 (1 Wt% SiC) were 0.23 W/m-K and 0.26 W/m-K respectively. And thermal conductivities of sample 3 (5 Wt% BeO) and sample 8 (5 Wt% SiC) were 0.26 W/m-K and 0.27 W/m-K respectively. After that, thermal conductivities of sample 4 (20 Wt% BeO) and sample 9 (20 Wt% SiC) were 0.35 W/m-K and

0.40 W/m-K. Thermal conductivities of sample 5 (40 Wt% BeO) and sample 10 (40 Wt% SiC) were 0.38 W/m-K and 0.42 W/m-K. At last thermal conductivity of sample 6 (60 Wt% BeO) was 0.45 W/m-K and of sample 11 (60 Wt% SiC) was also 0.45 W/m-K.

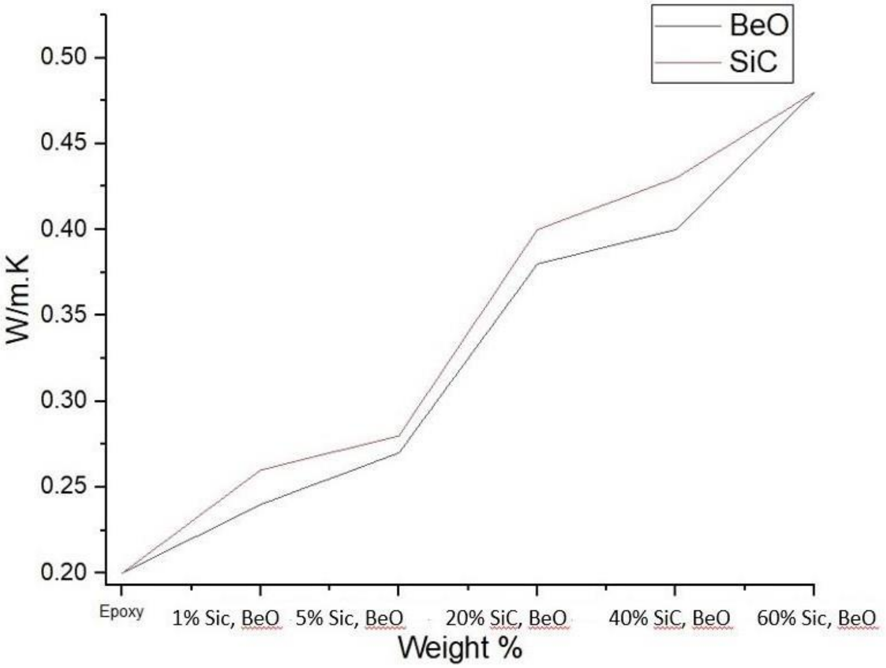

Figure 10 Values of thermal conductivity at room temperature

6.1.2 At 40°C–50 °C

At 40°C–50 °C, thermal conductivity of Sample 1 (epoxy) was 0.2 W/m-k and by increasing the amount of fillers the values of thermal conductivity were also increased. Thermal conductivities of sample 2 (1 Wt% BeO) and sample 7 (1 Wt% SiC) were 2.2 W/m-K and 2.3 W/m-K respectively. And thermal conductivities of sample 3 (5 Wt% BeO) and sample 8 (5 Wt% SiC) were 2.49 W/m-K and 2.49 W/m-K respectively. After that, thermal conductivitiesof sample 4 (20 Wt% BeO) and sample 9 (20 Wt% SiC) were 3.64 W/m-K and 3.5 W/m-K.

Thermal conductivities of sample 5 (40 Wt% BeO) and sample 10 (40 Wt% SiC) were 4.9 W/m-K and 5.3 W/m-K. At last thermal conductivity of sample 6 (60 Wt% BeO) was 6.32 W/m-K and of sample 11 (60 Wt% SiC) was also 6.5 W/m-K.

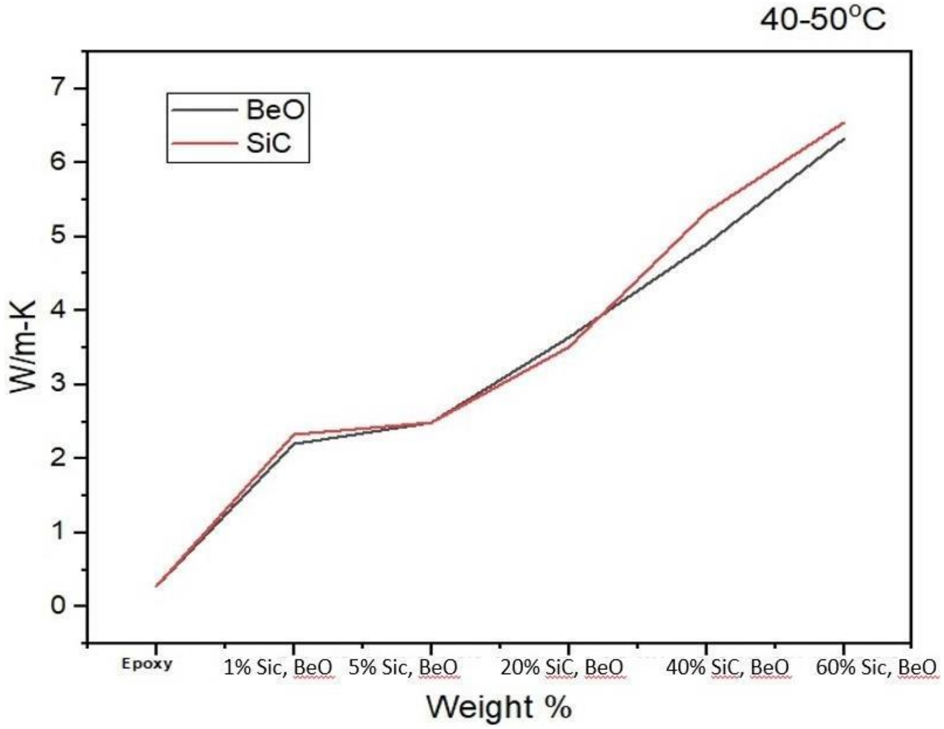

Figure 11 Values of thermal conductivity at 40°C-50°C

6.1.3 AT 70°C–80 °C

At 70°C–80 °C, thermal conductivity of Sample 1 (epoxy) was 0.2 W/m-k and by increasing the amount of fillers the values of thermal conductivity were also increased. Thermal conductivities of sample 2 (1 Wt% BeO) and sample 7 (1 Wt% SiC) were 2.5 W/m-K and 2.5 W/m-K respectively. And thermal conductivities of sample 3 (5 Wt% BeO) and sample 8 (5 Wt% SiC) were 2.51 W/m-K and 2.55 W/m-K respectively. After that, thermal conductivitiesof sample 4 (20 Wt% BeO) and sample 9 (20 Wt% SiC) were 4.1 W/m-K and 04.0 W/m-K.

Thermal conductivities of sample 5 (40 Wt% BeO) and sample 10 (40 Wt% SiC) were 5.75 W/m-K and 5.83 W/m-K. At last thermal conductivity of sample 6 (60 Wt% BeO) was 7.5 W/m-K and of sample 11 (60 Wt% SiC) was also 7.77 W/m-K.

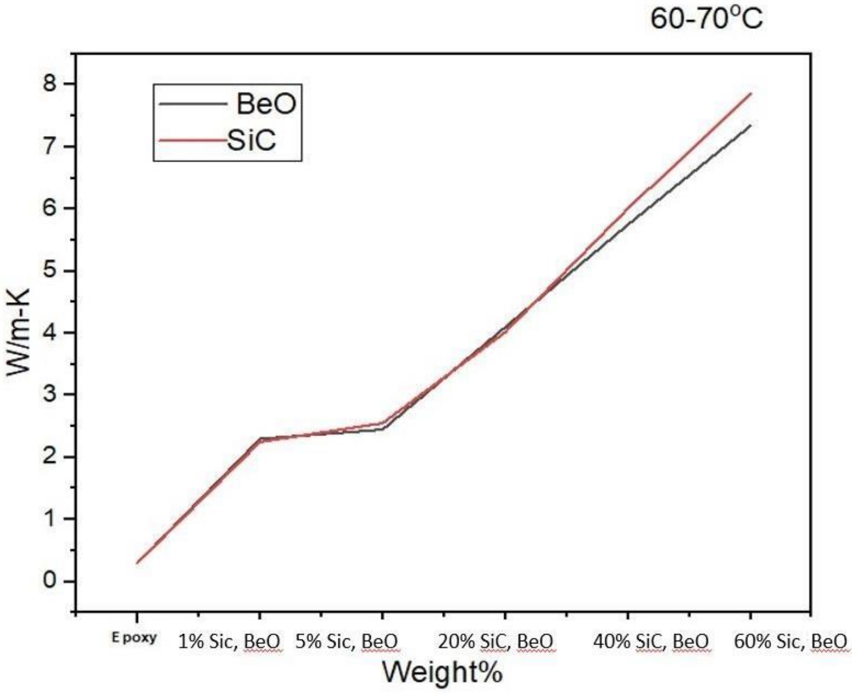

Figure 12 Values of thermal conductivity at 70°C-80°C

At higher temperatures, the thermal conductivity was increased due to heightened molecular motion and vibrational energy. As temperature rises, polymer chains exhibit greater mobility, facilitating more efficient heat transfer through increased phonon (vibrational) contributions. This leads to an overall enhancement in thermal conductivity at elevated temperatures. That's why the gradient of increment was higher at elevated temperatures. As BeO and SiC are bothmore thermally conductive than epoxy so increasing their amount resulted in higher values of thermal conductivity as heat will prefer the pat which has higher thermal conductivity. At all temperatures, sample 7 (5 Vol% SiC) has the best values of thermal conductivity so we can say that 7 (5 Vol% SiC) is most suitable sample according to this test.

6.1.4 Table of thermal conductivities of BeO samples

Table 1 Values of thermal conductivity of BeO samples at different temperatures

SAMPLES	25°C	40°C-50°C	60°C-70°C
SAMPLE 2 (1% BeO)	0.23 W/m-K	2.2 W/m-K	2.5 W/m-K
SAMPLE 3 (5% BeO)	0.26 W/m-K	2.49 W/m-K	2.51 W/m-K
SAMPLE 4 (20% BeO)	0.35 W/m-K	3.64 W/m-K	4.1 W/m-K
SAMPLE 5 (40% BeO)	0.38 W/m-K	4.9 W/m-K	5.75 W/m-K
SAMPLE 6 (60% BeO)	0.45 W/m-K	6.32 W/m-K	7.5 W/m-K
SAMPLE7 (1% SiC)	0.26 W/m-K	2.3 W/m-K	2.5 W/m-K
SAMPLE8 (5 % SiC)	0.27 W/m-K	2.49 W/m-K	2.55 W/m-K
SAMPLE9 (20%SiC)	0.40 W/m-K	3.5 W/m-K	4.0 W/m-K
SAMPLE10 (40%SiC)	0.42 W/m-K	5.3 W/m-K	5.83 W/m-K
SAMPLE11 (60%SiC)	0.45 W/m-K	6.5 W/m-K	7.77 W/m-K

6.2 Adhesion Test

Adhesion is crucial in thermal paste as it ensures optimal contact between surfaces, such as aCPU and a heat sink. This close contact improves heat transfer efficiency by minimizing air gaps. Effective adhesion helps eliminate voids, enhances thermal conductivity, and ensures better dissipation of heat, optimizing the overall cooling performance in electronic devices. We also conducted adhesion test by Universal Testing Machine. Again, there were total 11 samples as there were in thermal conductivity testing. Sample 1 comprised simple epoxy without reinforcement, while Samples 2, 3, 4, 5 and 6 featured 1%, 5%, 20%, 40% and 60%

weight of BeO, respectively. Similarly, samples 7, 8, 9, 10 and 11 incorporated 1%, 5%, 20%,40% and 60% weight of SiC whiskers.

The dimensions of area bonded were: 5mm X 10 mm. And by dividing the load at failure withthis bonded area we got values of adhesion for different samples. We formed a lap joint withAluminum slits and the thickness of adhesives were nearly 0.5 mm.

6.2.1 Samples containing BeO

Adding BeO played a vital role in improvement of mechanical interlocking, the adhesive strength of the epoxy matrix first improves as the amount of BeO increases. Sample 2's adhesive strength (1 Wt% BeO) is 4 N/mm2, whereas sample 3's adhesive strength (5 Wt% BeO) is 20.5 N/mm2. This rise makes sense given that BeO's high strength enhanced the mechanical interlocking. Additionally, sample 4's (20 Wt% BeO) adhesive strength is once again reduced to 8 N/mm2. And the adhesive strength of sample 5 (40 Wt% BeO) and sample 6 (60 Wt% BeO) comes out to be 7 N/mm2 and 6.3 N/mm2.

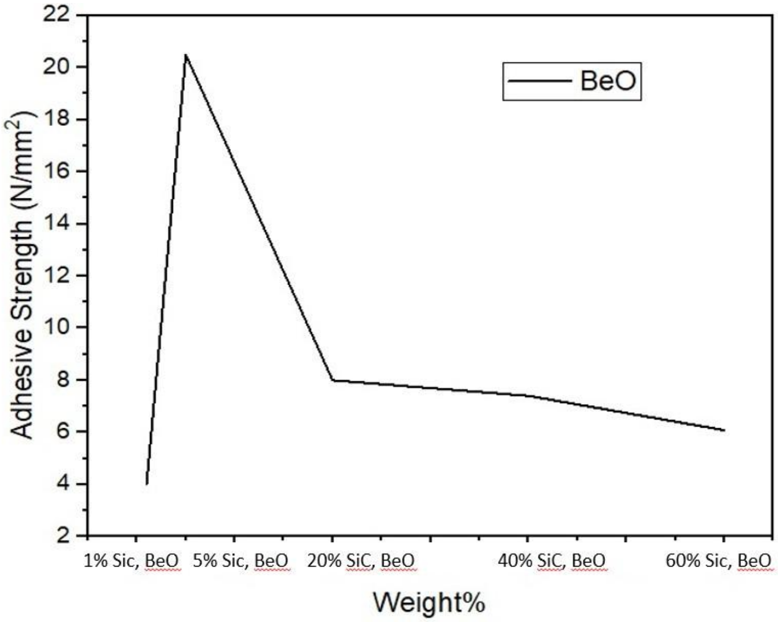

Figure 13 Adhesive strength of BeO reinforced samples

With an increase in BeO (Beryllium Oxide) content, epoxy's adhesive strength rose. This enhancement was credited to BeO's exceptional strength and mechanical qualities, which improved adhesive strength via improving mechanical interlocking. However, a decrease in adhesive strength was noted as the BeO concentration was raised further. This may be explained by BeO's innate brittleness and hardness. Although the first addition of BeOenhanced mechanical interlocking, too much of it reduced the epoxy's flexibility. This decreased pliability probably had a part in the adhesion strength decline. Ultimately, the beneficial impact on adhesive strength up to a specific concentration of BeO emphasizes how crucial it is to strike a compromise between the improved mechanical qualities and preserving the flexibility of epoxy.

Table 2 Adhesion strength of samples containing BeO

Samples	(wt% BeO)	Adhesive Strength (N/mm2)
Sample 2	1	4
Sample 3	5	20.5
Sample 4	20	8
Sample 5	40	7
Sample 6	60	6.3

6.2.2 Samples containing SiC whiskers

Adhesive strength of epoxy in literature = 1.5 N/mm2 - 3.5 N/mm

Sample 7's adhesive strength (1 Wt% SiC) is 9.6 N/mm2, whereas sample 8's adhesive strength (5 Wt% SiC) is 22 N/mm2. This rise makes sense given that SiC is a ceramic and has high strength which enhanced the mechanical interlocking. Sample 9's (20 Wt% SiC) adhesive strength is again increased to 36 N/mm2. And increasing the amount of Sic further resulted in decrease in adhesive strength and the adhesive strength of sample 10 (40 Wt% SiC) and sample 11 (60 Wt% Sic) comes out to be 30 N/mm2 and 28 N/mm2 respectively.

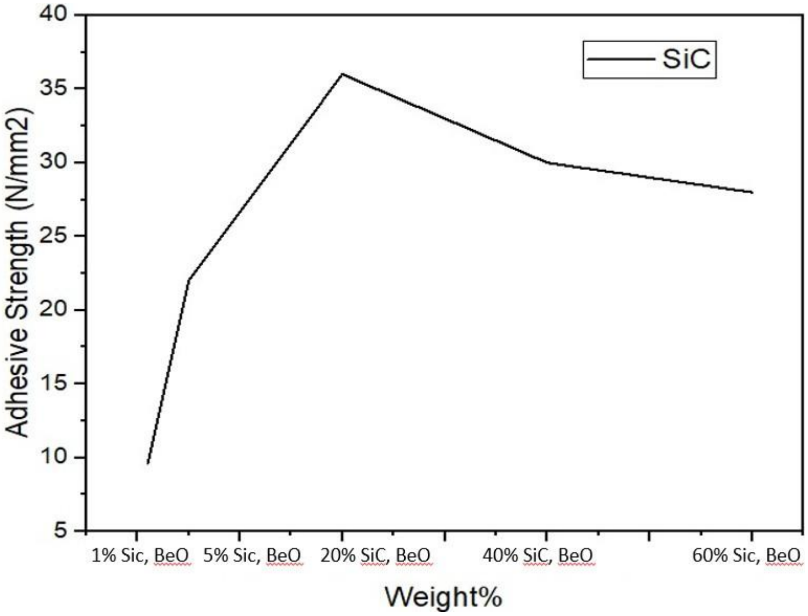

Figure 14 Adhesive strength of SiC reinforced samples

The adhesive strength of our epoxy matrix was further enhanced in the case of SiC whiskers by raising the content to 20 Wt% SiC. SiC did not cause our matrix to become brittle or lose its flexibility because it is far more flexible than BeO. Additionally, because of its higher strength,mechanical interlocking was enhanced, increasing total adhesion. Increasing the amount of SiC further resulted in a decrease in values of adhesive strength of our epoxy matrix. This is because after a threshold amount, even SiC starts to make our samples brittle that's why reduced flexibility resulted in reduced adhesive strength.

Table 3 Adhesion strength of samples containing SiC

Samples	**(wt% SiC)**	**Adhesive Strength (N/mm2)**
Sample 7	1	9.6
Sample 8	5	22
Sample 9	20	36
Sample 10	40	30
Sample 11	60	28

CHAPTER 7

COST ANALYSIS

As the demand for effective thermal management solutions in electronic devices increases, our group carried out a thorough cost analysis with an emphasis on the manufacturing of polymer-based thermal paste. Effective heat dissipation from electronic devices is essential for ensuring optimal performance and durability as they become more powerful and compact. By acting as essential constituents of thermal interface materials (TIMs), thermal pastes significantly enhance the pathway of heat from electronic components to heat sinks. We hopethat our cost study, which takes into account several aspects such raw material costs, manufacturing procedures, quality control procedures, and market dynamics, would offer useful insights into the production costs related to producing polymer-based thermal paste. We aim to optimize manufacturing processes, find potential cost-saving opportunities, and ultimately produce high-quality thermal paste solutions that satisfy the changing demands ofthe electronics industry while guaranteeing cost-effectiveness and competitiveness in the market by closely examining these cost components.

Our Calculated cost based on project estimation:

Table 4 Cost analysis per Kg in PKR

Materials	**Max Quantity Used**	**Price Per KG (PKR)**
Epoxy + Hardener	9g	6,000
BeO Powder	6g	70,000
SiC Powder	6g	85,000

Each sample weighed 10 grams and by all calculations we estimated and compared the cost of our thermal paste and commercially available thermal paste as:

Table 5 Comparison with commercially available thermal paste

ThermalPaste	**WeightPer Sample**	**Thermal Conductivity (W/m-K)**	**Price (PKR)**
Commercially available	10g	7-8	3,000
Our Paste	10g	7.7	600-800

CHAPTER 8

FUTURE OUTLOOK

8.1 Material Innovation

New polymer matrices and filler materials will be discovered as a result of ongoing research and development, improving the paste's stability, durability, and heat conductivity. More effective heat dissipation capabilities could be achieved by integrating advanced nanomaterials, leading to more effective thermal management solutions for electrical devices.

8.2 Reduce dependency on foreign countries

Manufacturers will work to lessen their dependency on imports from other nations by concentrating on domestic manufacturing and the sourcing of raw resources. This could entail forming alliances with regional vendors or constructing brand-new facilities for the extraction and processing of materials domestically.

8.3 Manufacturing Optimization

Production processes might be streamlined by automation and cutting-edge manufacturing techniques like additive manufacturing (3D printing), which would increase productivity, cut waste, and save manufacturing expenses. Consistent quality and scalability to fulfill increasing demand will be ensured by ongoing optimization.

8.4 Local Industry Development

The growth of the thermal paste manufacturing sector will open doors for nearby companies, promoting employment and economic development. Government incentives and supportivepolicies could promote the growth of domestic manufacturing capacity in this industry even further.

8.5 Market Expansion and Global Competitiveness

Manufacturers will aim to compete both domestically and abroad as the quality and performance of thermal paste produced domestically increases. These items will be more competitive in the global market because of strategic alliances, R&D expenditures, and compliance with international quality standards.

CONCLUSION

To sum up, the thorough assessment of thermal pastes through adhesion and thermal conductivity testing has yielded important information about their performance attributes. After extensive testing, it was shown that Sample 11, which included 60% of silicon carbide (SiC) whiskers, had better adhesion characteristics than Sample 6, which had 60% of beryllium oxide (BeO) particles, yet both samples had nearly the same thermal conductivity.According to this conclusion, Sample 11 is the best choice for the intended use. In addition, the results of the thermal conductivity testing indicated notable improvements in thermal performance at various temperatures. When compared to traditional thermal pastes, there was an amazing 125% increase in thermal conductivity at ambient temperature. In responseto temperature increases of 40°C–50°C and 70°C–80°C, respectively, the thermal conductivity values increased by 3150% and 3750%. These noteworthy advancements highlight how well the proposed thermal paste formulations facilitate heat transfer and increase thermal management capabilities, which makes them extremely attractive for a range of industrial and electronic applications.

REFERENCES

1. Raza, M.A., A. Westwood, and C. Stirling, *Graphite nanoplatelet/rubbery epoxy composites as adhesives and pads for thermal interface applications.* Journal of Materials Science: Materials in Electronics, 2018. **29**: p. 8822-8837.
2. Tang, D., et al., *Preparation and properties of epoxy/BN highly thermal conductive composites reinforced with S i C whisker.* Polymer Composites, 2016. **37**(9): p. 2611-2621.
3. Swamy, M.K. and Satyanarayan, *A review of the performance and characterization of conventional and promising thermal interface materials for electronic package applications.* Journal of Electronic Materials, 2019. **48**(12): p. 7623-7634.
4. Norazlina, M., S. Shanmugan, and D. Mutharasu, *Structural analysis of BeO nanoparticles synthesized by polyacrylamide gel route.* Advanced Science Focus, 2013. **1**(4): p. 362-366.
5. Fu, Y.-X., et al., *Thermal conductivity enhancement with different fillers for epoxy resin adhesives.* Applied Thermal Engineering, 2014. **66**(1-2): p. 493-498.
6. Allen, R. and P. Sanderson, *Characterization of epoxy glues with FTIR.* Applied Spectroscopy Reviews, 1988. **24**(3-4): p. 175-187.
7. Akishin, G., et al., *Thermal conductivity of beryllium oxide ceramic.* Refractories and Industrial Ceramics, 2009. **50**(6): p. 465-468.
8. Rau, R., *X-ray Diffraction Investigation of BeO Calcination Processes.* Advances in X-Ray Analysis, 1960. **4**: p. 19-39.