Chapter 2

# A Study on Synergizing Strength of Thermoplastic Composites Modified with Waste Ceramic and Metal

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**Abstract**

The realm of research and development in environmentally sustainable materials assumes a paramount role in contemporary industry, aligning with concerted environmental conservation initiatives. Within this landscape, thermoplastic composite materials, enriched with waste ceramics and laden with metallic fillings, command attention due to their unique amalgamation of superior mechanical attributes and an unwavering commitment to ecological integrity. The repertoire of waste ceramics encompasses industrial remnants or ceramics earmarked for recycling, embodying a conscientious approach to resource optimization. Analogously, the metal fillings are derived from recycling processes, reflecting a broader commitment to sustainable material sourcing.

The synergy achieved by combining waste ceramics and metal fillings represents a significant leap forward in resource efficiency, concurrently mitigating adverse environmental impacts. The introduction of ceramic additives imparts heightened resistance to elevated temperatures by mitigating the material's thermal expansion coefficient. In contrast, metal fillings contribute to augmented mechanical robustness, endowing the material with heightened tensile strength. These attributes render the materials particularly

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advantageous for diverse applications in industries such as automotive, aerospace, and construction.

Moreover, the recyclable nature and environmentally friendly composition of these composite materials underscore their pivotal role in environmental conservation, mitigating detrimental impacts. In essence, waste ceramic-added and metal-filled thermoplastic composite materials epitomize a harmonious blend of high mechanical prowess and ecological consciousness. Consequently, these materials emerge as an optimal choice for industrial utilization, offering a synthesis of robust mechanical properties and environmentally considerate structures.

## 1.Introduction

Thermoplastics, colloquially referred to as 'plastics,' represent a class of polymers distinguished by their capacity to undergo melting and reshaping upon exposure to heat. These materials, amenable to processes like injection molding and extrusion, exhibit unique properties during both their molten and solid states. During the cooling phase in manufacturing or molding, thermoplastic polymers typically evade the formation of an ordered crystal structure, primarily attributable to the intricate configuration of polymer chains predisposed to curling and contraction. The formation of a regular crystal lattice demands a considerable input of energy due to the complex nature of these chains.

The constituent chains of thermoplastics commonly manifest a semi-crystalline structure, amalgamating amorphous and crystalline attributes rather than adopting a pristine crystal lattice. This hybrid structure imparts elasticity from the amorphous regions and augments strength and rigidity through crystalline elements. The delineation of this semi-crystalline structure relies on the melting point (Te) within the crystallizing chains, while amorphous thermoplastics or segments within thermoplastics are characterized by the glass transition temperature (Tg). Beyond the melting point, the entire crystal structure within the polymer dissolves, leaving behind only the amorphous structure.

Thermoplastic polymers are characterized by specific glass transition temperatures (Tg) and an expansive melting temperature range in those encompassing crystal structures. The polydisperse nature of these polymers contributes to a broad melting curve, indicative of diverse defects or unit cells within the crystal lattice. Techniques such as X-ray analysis are employed to elucidate this intricacy. The chain architecture of thermoplastic polymers is typically linear or branched, with a notable absence of cross-links between chains. The capacity for melting and reshaping defines a thermoplastic, and any introduction of cross-covalent bonds resulting from external factors marks a departure from this classification, a transformation more commonly associated with thermosetting polymers (1–3).

In contrast to thermoset polymers, thermoplastic polymers lack covalent bonds between their chains but are intricately bound by a network of intra- and inter-chain interactions. These interactions include polar attractions, hydrogen bonding, London dispersion forces, and stacking of aromatic groups, which collectively contribute to the structural integrity of the material. Furthermore, intra-chain and inter-chain twists and entanglements play a crucial role in maintaining the cohesion of thermoplastic polymer chains. These intricate molecular arrangements, characterized by circulations and bends, exert a profound influence on the physical properties of thermoplastic polymers, particularly in terms of mechanical responsiveness.

Distinguishing themselves from elastomers, thermoplastics exhibit distinct mechanical properties. Elastomers demonstrate rapid elongation under tensile stress, reverting to their original position upon force removal, a phenomenon known as elasticity. In contrast, thermoplastics retain elasticity up to a certain point when stretched, ultimately undergoing permanent deformation or fracture. Notably, thermoplastics require higher forces for elongation compared to elastomers, indicating their heightened resistance to deformation.

The tensile strength and elastic modulus of elastomers, such as natural rubber, typically fall within the range of 15 MPa and 10 MPa. In contrast, thermoplastics display considerably higher values at 37 MPa and 800 MPa, respectively. An essential characteristic of thermoplastics is their capacity for enduring permanent deformation under load, facilitating a lasting change in shape under applied force, exemplified by thermoforming methods. The semi-crystalline structure inherent in thermoplastics enables a transition from a rigid to a pliable state at a specific temperature, determined by the amorphous regions within (glass transition temperature).

This thermal transition not only governs the applications of plastics but also influences the manufacturing processes. For instance, the choice of polymer with a high or low glass transition temperature dictates the suitability for specific uses, such as mobile phone cases requiring a rigid structure or electrical cables necessitating flexibility. Additionally, the glass transition temperature influences production processes, with the incorporation of plasticizer additives aimed at enhancing the formability of thermoplastics or reducing the required processing temperature to conserve energy.

Following the synthesis of thermoplastic polymers, the resultant materials are typically packaged and commercialized in the form of small granules. Purchasers possess the capability to employ diverse production techniques to melt, mold, or extrude these granules into various forms, exemplifying the versatility of thermoplastics. Commonly utilized in the production of items such as plastic cups, bags, packaging materials, and toys, thermoplastics find widespread application across diverse sectors. Importantly, the recyclability of these materials allows for their repeated use, aligning with sustainable practices.

In applications emphasizing transparency, preference is often given to amorphous thermoplastics, exemplified by materials such as PMMA (polymethyl methacrylate) or polycarbonate. Amorphous thermoplastics, characterized by their lack of a regular crystal structure, are well-suited for applications where clarity is paramount. However, it is crucial to note that amorphous thermoplastics typically exhibit lower resistance to chemicals and are susceptible to environmental stress cracking.

Conversely, semi-crystalline thermoplastics demonstrate enhanced resistance to solvents and chemicals but possess an opaque structure due to larger crystal sizes exceeding the wavelength of light. Consequently, they are not favored in optical applications. Prominent examples of thermoplastic polymers include polycarbonate, poly(vinyl chloride), polyethylene, polypropylene, and polystyrene. These polymers, distinguished by their diverse chemical compositions, cater to a broad spectrum of industrial applications, underlining their ubiquity and preference across various industrial domains(1,4,5).

## 1.1 Post-Synthesis Utilization of Thermoplastic Polymers: Applications and Characteristics

### 1.1.1 PC (Polycarbonate: An Insight into a High-Performance Thermoplastic)

Polycarbonate, a high-performance thermoplastic renowned for its low specific gravity, stands out as an engineering plastic distinguished by a myriad of exceptional properties. Characterized by high impact resistance, low moisture absorption, commendable thermal insulation, and stability in both molten and oxidative states, polycarbonate holds a significant position among commercial polymers. While it is commonly synthesized from bisphenol A (BPA), an alternative synthesis route involving phosgene is also feasible.

Polycarbonate derived from BPA exhibits notable impact resistance, making it a preferred choice for optical applications, notably in eyeglass lenses. Its transparency and superior light transmittance contribute to its prominence in optical items. However, its susceptibility to scratches necessitates the application of a thin protective film on its surface. Innovations in polycarbonate formulations, incorporating reactive compounds or epoxies, are being explored by eyeglass manufacturers as an alternative to traditional film coating methods.

In comparison to polymethylmethacrylate (PMMA) plastic, polycarbonate demonstrates heightened strength and a broader temperature range but comes with an elevated cost. The vitrification temperature of polycarbonate is approximately 150°C, with fluidity manifesting above 300°C. Commercial products are commonly fabricated through injection molding and extrusion methods, with the ease of production influenced by the molecular weight of the polycarbonate.

It's noteworthy that another variant of polycarbonate, specifically employed in ultralight optical devices, is synthesized from a carbonate monomer featuring allyl groups at both ends, rendering it a cross-linked thermoset polycarbonate. Unlike the BPA-based thermoplastic, this variant cannot be melted upon heating but undergoes decomposition. Despite this limitation, it boasts a higher refractive index than glass, facilitating the production of thinner components with robust mechanical properties and exceptional heat resistance.

The versatility of polycarbonate finds expression in an array of applications, particularly in the production of digital devices and electronic goods such as CDs and DVDs. Its application extends to items requiring resistance to shattering, including protective components for sports equipment, medical devices, as well as bottles and food storage containers. In summary, polycarbonate stands as a widely utilized material in the manufacturing landscape, particularly in the realm of digital technology and items demanding a combination of durability and transparency(4–7).

### 1.1.2 PVC (Polyvinyl Chloride: Composition, Characteristics, and Industrial Applications)

Polyvinyl chloride, commonly known as PVC, stands as the third-largest thermoplastic polymer in use, finding extensive applications across diverse industries ranging from toy manufacturing to the production of construction materials. The manufacturing of PVC predominantly employs the suspension polymerization method, involving the polymerization of vinyl chloride monomers to yield a polymer characterized by a low crystal structure. The incorporation of large chlorine groups results in a robust and resistant molecular arrangement, contributing to PVC's durability.

However, PVC exhibits sensitivity to light and heat, representing a notable drawback. Under conditions of elevated temperature or prolonged exposure to light, PVC may release hydrogen chloride (HCl) molecules into its surroundings, potentially leading to the decomposition of surrounding materials and posing health risks. The inherent instability of PVC and related halogenated polymers is mitigated through the incorporation of additives, and ongoing efforts focus on developing solutions to minimize or eliminate adverse environmental impacts.

PVC's intrinsic hardness and toughness, stemming from its favorable mechanical properties, contribute to its wide-ranging applicability. The incorporation of plasticizer additives further enhances its versatility, enabling the modification of PVC into a flexible form. Coupled with rubber plastics, PVC achieves increased impact resistance. Despite its colloquial reference as "vinyl," it is essential to recognize other polymers within the vinyl family, including polyvinyl acetate, polyvinylidene chloride, and polyvinyl alcohol.

Various plasticizing additives, such as diisooctyl phthalate, tritolyl phosphate, and epoxidized oils, play a crucial role in PVC modification. These additives interpose between PVC chains, facilitating their movement and functioning akin to an "internal lubricant." The role of these additives in PVC mirrors the functions performed by polystyrene copolymers and polymer blends in analogous manners, showcasing the intricate balance and chemical dynamics involved in tailoring PVC for diverse industrial applications(2,8–10).

### 1.1.3 PE (Polyethylene in the Commercial Polymer Landscape: A Overview)

Polyethylene holds a preeminent position among commercial polymers, boasting a global capacity and capital capacity of 134.11 million tonnes in 2022. This sector is poised for continued growth, with a projected Average Annual Growth Rate (AAGR) surpassing 7% until 2027. Key players in polyethylene production, including China, the USA, Saudi Arabia, South Korea, and India, collectively contribute to a substantial 100 million tons of the global output, constituting 53% of total polyethylene capacity by 2022. This prolific production is a driving force behind polyethylene's extensive applications spanning various sectors(11,12).

Originating from petroleum, polyethylene is a thermoplastic polymer broadly categorized into two main classes: Low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE). LDPE, synthesized through radical chain polymerization, exhibits greater molecular branching compared to HDPE. These branchings, whether short or long, influence LDPE properties. The high degree of branching impedes the formation of a crystal structure, resulting in lower crystallinity (40-60%) compared to HDPE. Additionally, branching reduces density, with LDPE densities ranging from 0.9 to 0.93 $g.cm^{-3}$. LDPE, with a glass transition temperature (Tg) of approximately 120°C and a melting temperature around 110°C, demonstrates flexibility over a broad temperature range. Commercial (13–15) varies in number average molecular weight (20-100 $kg.mol^{-1}$) and molecular weight distribution (3-20), providing diverse properties determined by factors such as reactor type, polymerization temperature, and pressure.

In contrast, the production of High Density Polyethylene (HDPE) utilizes Ziegler-Natta and Philips-type reactive initiators, resulting in reduced branching and high polymer conversion. This reduction in branching facilitates the formation of an ordered crystal structure, leading to higher crystallinity (70-90%) and a crystal melting temperature of approximately 135°C for HDPE.

HDPE's versatility is evident in its widespread applications, with 40% attributed to plastic parts produced by air blow molding, 30% to parts manufactured through injection molding, and the remaining percentage to products created via the extrusion method. These applications span diverse industries, including beverage and food containers, kitchenware, pipes, tubes, cables, and cleaning product bottles. The unique properties and production methodologies of LDPE and HDPE enable tailored usage across an array of markets, solidifying polyethylene's position as a cornerstone in industrial materials(16–19).

### 1.1.4 PS (Polystyrene: An Economical and Versatile Thermoplastic Polymer)

Polystyrene, an economical and robust thermoplastic polymer, finds extensive utility across a diverse spectrum of applications. Characterized by an aromatic polymer chain, polystyrene is synthesized from the aromatic styrene monomer, a liquid hydrocarbon molecule derived from the petrochemical industry. Among the most encountered plastics in daily life, polystyrene holds the distinction of being the second most widely used plastic after polyethylene. Its thermoplastic nature allows for facile processing and molding through heating and cooling, contributing to its versatility. Solid at room temperature, polystyrene lends itself to the production of a myriad of products with desired shapes through molding and cooling at elevated temperatures. Notably, CD and DVD covers exemplify applications wherein polystyrene is molded to achieve specific shapes. Pure solid polystyrene is inherently transparent, yet the inclusion of pigments during production enables the creation of polystyrene in various colors. Additionally, the production of polystyrene foam, commonly seen in white water glasses and numerous daily-use products, is another testament to its adaptability. Expressed with the formula $(C_8H_9)n$, polystyrene is formed by attaching a phenyl group to every second carbon on a lengthy hydrocarbon chain. Its synthesis from a vinyl-based monomer involves free radical vinyl polymerization, yielding isotactic polystyrene (iPS). Despite the potential advantages of iPS, its industrial production is relatively uncommon due to the superior properties offered by other crystallizable polymers. Moreover, the cost-effectiveness of isotactic polypropylene or polyethylene synthesis tends to make them more favorable alternatives in industrial settings.

Polystyrene, recognized for its economical nature and robust thermoplastic attributes, presents a diverse range of applications. Its molecular structure, originating from the aromatic styrene monomer derived from the petrochemical industry, contributes to its status as one of the most commonly encountered plastics in daily life, following polyethylene in prevalence. As a thermoplastic polymer, polystyrene can be efficiently processed and molded through heating and cooling, enabling its utilization in various industries. While isotactic polystyrene (iPS) possesses a crystal structure, it tends to be brittle and challenging to process. Atactic polystyrene (atactic PS), the more commonly produced form, is amorphous due to the disorder introduced by atacticity, eliminating a melting point. Despite its inability to crystallize, atactic PS is crucial in engineering plastics. Copolymerization with polybutadiene during polymerization results in a copolymer known as high impact polystyrene (HIPS). The macro-phase separation in this copolymer, with polybutadiene globules enhancing impact resistance, transforms the traditionally brittle polystyrene into a more durable material. Polystyrene exhibits inertness to chemical reactions, showcasing resistance to alkali metals, halogen acids, and various reducing and raising compounds. However, exposure to certain solvents can compromise its integrity. While polystyrene has excellent optical properties, such as easy coloring, transparency, and clarity, its mechanical properties, including brittleness and low heat deflection temperature (HDT), make it less suitable for certain applications, such as those requiring sterilization for healthcare use. Copolymers of polystyrene, especially styrene-butadiene synthetic rubbers, find significant application, particularly in latex-based paints. Styrene-butadiene copolymers, often comprising 60% styrene and 40% butadiene by weight, play a crucial role in the thermoplastic elastomer market. Introducing copolymers like acrylonitrile and fumaronitrile enhances properties like heat and impact resistance while preserving styrene's desirable characteristics. Another notable development is the Acrylonitrile Butadiene Styrene (ABS) polymer, widely used in the automotive sub-industry. ABS resin integrates a rubber-reinforced polymer matrix with a glassy matrix containing polystyrene and styrene-acrylonitrile copolymer. The elastomeric rubber component is the styrene-butadiene copolymer, contributing to ABS's superior resistance to high temperatures and chemical solvents compared to High Impact Polystyrene (HIPS). Unlike other plastic materials, ABS can be cold-formed, akin to metals, marking it as an exceptional engineering plastic material. The production of polystyrene in a foamy form is accomplished through the suspension polymerization method, a technique that introduces a blowing agent into the system. In this transformative process, the high heat generated during the reaction serves a dual purpose: softening the polystyrene resin and evaporating the added blowing agent. This dual action results in the creation of a spongy or foam-like structure within the polystyrene resin, yielding a material with distinct properties conducive to various applications (20–26).

### 1.1.5 PA (Polyamides: A Fusion of Nature and Industry)

Polyamides, members of the polyamide class, arise from the bonding of monomers containing repeating units of acid and amine groups through amide bonds. While nature's polyamides encompass proteins, wool, and silk, synthetic counterparts, such as nylon and aramid, have been engineered in laboratories. Among synthetic polyamides, nylon stands out as a prominent engineering polymer with applications spanning the textile industry, musical instrument strings, and various other fields. Despite being thermoplastic polymers, polyamides are predominantly employed in the fiber industry, where their key properties shine. These properties include exceptional resistance to wear and tear, robust mechanical characteristics at elevated temperatures, low gas permeability, and resistance to chemicals. Notably, more than 60% of produced nylon is utilized in the form of fibers. The discovery of nylon by DuPont in 1935 marked a pivotal moment in polymer history. Initially employed as bristles in toothbrushes, nylon rose to commercial prominence in the 1940s when it began replacing silk in women's socks due to its silky texture. The scarcity of silk during World War

II further fueled the adoption of nylon, leading to significant advancements in polymer science and industry. Nylon played a crucial role in wartime applications, featuring in parachutes, military ropes, and tires.

Beyond its role in the fiber industry, nylon serves as a versatile polymer for the production of solid-state mechanical parts. It has become a preferred material over metals, particularly in components subjected to low and medium forces, such as impellers and screwed parts. In engineering-grade formulations, nylon undergoes processing through extrusion, pour molding, and injection molding methods. For applications requiring heightened structural strength, impact resistance, and stiffness, nylon composites enter the scene. Reinforced with glass particles or fibers, these composites enhance the material's overall performance. For instance, nylon composites, especially those fortified with 25% glass fiber, find application in the automotive industry, notably in components like engine semi-parts, thanks to their remarkable heat resistance. Aramid, a distinguished member of the polyamide class, stands out from nylons due to the presence of aromatic groups in its chain backbone. Renowned for exceptional strength, aramid fibers, known by brand names such as Kevlar and Nomex, find application, especially in ballistic scenarios, owing to their remarkable properties. These fibers not only exhibit outstanding strength and Young's modulus but also showcase excellent heat and fire resistance attributed to their aromatic groups. Polyamides, including aramids, are synthesized through the condensation polymerization mechanism. Unlike polyesters, strong acids are not utilized in the synthesis of polyamides, as the reaction rate is inherently high. The commonly employed method involves the direct amidation of diacids with diamine. For instance, Nylon6,6 polyamide is crafted through the reaction of hexamethylene diamine and adipic acid. The regular and symmetrical chain backbone of polyamides facilitates easy crystallization. While polyamides are semi-crystalline polymers with approximately 50% crystal structure in the standard production process, the application of mechanical tension increases the crystal structure ratio in resulting fibers. Nylon6,6, a noteworthy polyamide, boasts moderate crystallinity, combining sought-after properties such as strength, flexibility, toughness, wear resistance, colorability, low coefficient of friction (self-lubrication), low creep, and resistance to solvents. Despite its impressive attributes, the primary drawback of Nylon6,6 is its susceptibility to moisture, leading to a decline in dimensional and mechanical properties in humid environments. The mechanical strength of polyamides, including Nylon6,6, stems from the interactions between chains, specifically through hydrogen bonding. Though individually considered weak compared to covalent bonds, the multitude of interchain hydrogen bond interactions collectively forms a robust secondary force. These hydrogen bonds contribute to the crystallization of polymer chains, allowing polyamides to possess a highly crystalline structure and, consequently, high mechanical strength(27,28). However, the hydrogen bonds in polyamides are susceptible to disruption in humid environments, leading to a loss of interchain interaction. Water molecules, characterized by a polar structure akin to polyamide chains, possess the ability to disrupt interactions between polyamide chains, consequently increasing the mobility of these chains. Despite the disruptive influence of water molecules, polyamides do not dissolve in water. Instead, water induces swelling and softening in polyamides, effectively plasticizing them. Consequently, polyamides are susceptible to mechanical and dimensional degradation in humid environments. The recommended temperature range for the continuous use of polyamides is 65-75°C for pure polyamides and 100-115°C for polyamide composites reinforced with glass and other minerals. However, polyamides can retain their mechanical properties at temperatures up to 150°C. While commonly used polyamides such as nylon6 and nylon6,6 exhibit similar properties, nylon6 has a lower melting point at 223°C, while nylon6,6 boasts a melting temperature of approximately 255°C. Beyond nylon6 and nylon6,6, various polyamides have been developed, including Nylon6,9, Nylon6,10, Nylon6,12, Nylon11, Nylon12, Nylon12,12, and Nylon4,6. Polyamides with more methylene groups than nylon6 or nylon6,6 generally demonstrate increased moisture resistance, dimensional stability, and improved electrical properties. However, nylons with higher methylene groups often exhibit lower crystallinity and mechanical properties. Polyamides are typically insulating materials, yet they tend to generate static electricity at high voltage and frequency, potentially leading to hazardous sparks(29). As a result, the use of polyamides is generally restricted to low-frequency applications. To mitigate this electrical sensitivity, conductive particles such as carbon black or silver can be added to polyamides, enhancing their suitability in various settings(27,30,31).

### 1.1.6 PP (Polypropylene: A Versatile Thermoplastic Polymer)

Polypropylene, the preeminent commercial thermoplastic polymer, reached global production levels of 45 million tons in 2001, establishing a market valued at $65 billion. Isotactic polypropylene (iPP) boasts an exceptional strength-to-weight ratio, attributed to its low density and high strength. These properties render it the polymer of choice in diverse applications, ranging from automotive components to the textile and packaging industries(32).

Synthesized through the polymerization of propylene monomers derived from gases obtained in olefin facilities and oil refineries, polypropylene can adopt isotactic, syndiotactic, or atactic conformations, with each conformation influencing crystal structure, ratio, and density. While atactic polypropylene struggles to form a crystal structure, isotactic polypropylene can crystallize more effectively than LDPE but falls short of achieving the density of HDPE crystal structures. In essence, the crystal ratio of polypropylene fluctuates between 40% and 70%.

Polypropylene, known for its toughness and flexibility, has evolved into an engineering plastic, particularly when copolymerized with ethylene, often replacing ABS. The melting point of polypropylene crystals hovers around 160 degrees Celsius, with typical processing temperatures exceeding 200 degrees Celsius. Common production methods for polypropylene parts include injection molding and blow molding.

The melt flow index (MFI), a crucial parameter in the production phase, directly correlates with the molecular weight of polypropylene. MFI values provide insights into the ease of processing a plastic material, where higher MFI values indicate better mold-fillability. However, increasing MFI may compromise some physical properties, such as impact resistance.

Polypropylene exhibits sensitivity to UV rays and high temperatures during heat treatment. UV-absorbing additives, like carbon black, can extend the polymer's life by shielding it from UV rays. Additionally, antioxidant additives prevent polypropylene from degrading at elevated temperatures during molding processes.

Polypropylene is produced in three primary forms: homopolymer, copolymer, or block copolymer. Copolymers often incorporate ethylene as a co-monomer, yielding ethylene-propylene rubber. This copolymer significantly enhances impact resistance at low temperatures. Moreover, the random arrangement of ethylene monomers reduces the crystallinity of polypropylene, resulting in a more transparent plastic(33–35).

### 1.1.7 PET (Polyethylene Terephthalate: A Fundamental Thermoplastic Polymer)

Polyethylene terephthalate (PET), constituting 18% of global plastic production, ranks third after polyethylene and polypropylene. It is widely recognized and utilized in various daily applications, often referred to by the abbreviation PET but also designated as PETE, PETP, or PET-P. As a linear thermoplastic polymer belonging to the polyester group, PET finds applications in synthetic fibers, food packaging, and particularly bottling.

PET materials are shaped through thermoforming, comprising pure PET polymer or, in some instances, reinforced with glass fiber for engineering applications. PET, a significant commercial polyester, was introduced to the market in 1944. Its name originates from containing both an ethylene group and a terephthalate group in its repeating unit. The synthesis of high molecular weight polyesters, unlike polyamides such as nylon, involves the esterification reaction of a diacid and a diol. Commercially, the transesterification reaction is often followed, reacting dimethyl terephthalate with ethylene glycol to obtain bis-(2-hydroxyethyl) terephthalate and methanol. This is followed by further reactions to obtain PET and ethylene glycol products, with the latter being reusable. PET can be synthesized by various chemical methods or undergo different heat treatments post-synthesis, resulting in either a completely amorphous or semi-crystalline structure. PET with an amorphous structure yields transparency, while semi-crystalline PET can be transparent or opaque depending on crystal size and structure. Commercially synthesized PET may have a crystal structure of up to 60%, with an average melting temperature around 270 °C. Despite preferring a crystalline state, PET is not a polymer that crystallizes easily, impacting its inclusion among engineering plastics. Its long crystallization time increases molding costs, but additives are employed to expedite the process. With a high melting point of 270°C, PET exhibits a hard chain backbone, providing advantages such as high strength, toughness, and resistance up to 150°C. Its low specific gravity allows for variable hardness depending on thickness. PET is durable, impact-resistant, and offers good barrier properties against gases, solvent chemicals, and alcohols, albeit with less moisture resistance compared to some other plastics. the utilization of Polyethylene Terephthalate (PET) is extensive, particularly in the realm of plastic bottles due to its robust barrier properties. To enhance its barrier efficacy, PET can be compounded with poly(vinyl alcohol), offering superior barrier characteristics, especially in scenarios where oxygen permeability is of paramount concern. Notably, oriented PET films exhibit prominence in applications necessitating robust mechanical strength. These films, when oriented bidirectionally and aluminized, manifest an opaque and reflective surface, finding substantial application in the packaging industry for the fabrication of flexible packages. The versatility of PET extends to tape applications, leveraging its noteworthy mechanical strength. Instead of employing PET in its unadulterated state, a more rigid composite material can be derived by fortifying it with glass particles or fibers. While PET is commonly deployed as a linear thermoplastic homopolymer, its fortification can also be achieved through copolymerization. The introduction of the cyclohexane dimethanol group to the polymer backbone, as opposed to ethylene glycol, mitigates cohesion among PET chains and disrupts the crystal structure, leading to the advent of a novel copolymer known as PETG. By 2001, the global production of PET reached approximately 30 million tons, with 45% allocated to fiber applications. PET fibers exhibit remarkable resistance to wrinkles and abrasion, and their incorporation in textile products, particularly in tandem with cotton or cellulose-based fibers, imparts enhanced moisture resistance and a tactile sense of naturalness. In fiber form, PET finds application in diverse domains, encompassing curtains, clothing, upholstery fabrics, tire strips, and industrial filtration processes. Given its adeptness as a gas barrier, 10% of produced PET polymers are channeled into the food and beverage packaging sector, notably in bottling applications. PET's role extends to film applications, prominently featured in photographic films, magnetic and X-ray tapes, and electrical insulation contexts. Beyond these applications, PET emerges as a pivotal material in electronic devices, office equipment, and automotive components, progressively supplanting traditional metals like steel and aluminum in various engineering applications. PET's mechanical robustness and hardness undergo augmentation through compounding with materials such as glass fiber, silicone, graphite, or Teflon. Noteworthy examples include glass fiber-reinforced PET composites, well-suited for sustained use at elevated temperatures, reaching up to 150°C. This confluence of material science and engineering applications underscores the multifaceted significance of PET in diverse industrial landscapes(36–41).

### 1.1.8 PMMA (Molding the Future: Polymethylmethacrylate in Automotive, Optics, and Beyond)

Polymethylmethacrylate (PMMA), commonly recognized as acrylic glass or plexiglass in the market, stands out as a colorless and transparent thermoplastic polymer. Frequently employed as a viable substitute for glass and an alternative to polycarbonate due to shared properties, PMMA is valued for its economic efficiency and ease of processing, despite having a relatively fragile structure. Its synthesis from methyl methacrylate monomer primarily employs the radical chain growth polymerization method, although anionic polymerization is also feasible. The commercial form of PMMA is a linear polymer characterized by a 70-75% syndiotactic chain structure, yet its lack of complete stereo-regularity and the sizable methacrylate groups contribute to its amorphous nature, precluding crystallization. The glass transition temperature hovers around 105°C. PMMA's distinctive feature lies in its remarkable optical transparency, coupled with resilience to external weather conditions, rendering it suitable for applications emphasizing light transmittance. However, its susceptibility to scratches restricts its use in optical domains, despite attempts with various additives to address this issue resulting in a compromise on mechanical properties. Nevertheless, PMMA surpasses glass in transparency, maintaining its translucency even in thicknesses up to 35 cm. With a tensile strength reaching 70 MPa and impact resistance nearly comparable to High Impact Polystyrene (HIPS), PMMA is a machinable plastic. The heat-resistant variant of PMMA achieves a load bending temperature (HDT) surpassing 90°C, constituting a generally malleable plastic. While it exhibits resistance to many chemicals, it is not impervious to organic solvents. Injection-molded PMMA parts find application in diverse sectors, including automotive headlights, appliance covers, optical equipment, and home decoration products. Additionally, PMMA lends itself to the production of acrylic-based sheets. Beyond pure PMMA, copolymers involving ethyl acrylate and metal methacrylate monomers contribute to the production of thermoset resins. The industry predominantly employs acrylate/methacrylate copolymers synthesized from varying combinations, attesting to the versatility of acrylic plastics in industrial applications(42–48).

### 1.1.9 PEK-PEEK (High-Performance Polymers for Demanding Industrial Applications)

Polyketones belonging to the aromatic polyether class stand out as high-performance polymers of significant industrial importance. Predominantly represented by poly(ether ether ketone) (PEEK) and poly(ether ketone) (PEK), these polyketones find extensive utilization in critical sectors such as the aircraft and automotive industries, owing to their exceptional durability. Operating seamlessly within the temperature range of 240-280°C, these polymers exhibit robust resistance to elevated temperatures and chemical corrosion. Characterized by a semi-crystalline structure with a substantial 35% crystalline region, PEEK crystals undergo melting at 340°C, while PEK exhibits a higher melting point around 360°C. The vitrification point of PEEK is reached at approximately 140°C, whereas PEK requires heating to a higher temperature, up to 165°C, to surpass its vitrification threshold. The elevated glassification temperatures of these polyketones are attributed to their rigid structure, where phenyl groups impose constraints on molecular movement, facilitating crystal formation. The increased hardness of the carbonyl group in PEK, compared to the ether group, imparts reduced flexibility to the PEK chain, resulting in a higher glassification temperature. Both PEEK and PEK demonstrate remarkable resistance to high-temperature degradation and chemical influences, akin to polyamides and polysulfones in organic solvents and aqueous environments, respectively. However, PEEK exhibits solubility limitations, being soluble only to a restricted extent in specific high-evaporation-point polar organic solvents such as pyrene or benzophenone. The insolubility of PEEK in organic solvents constrains chemical modifications of its polymer chain. Notably, PEEK manifests sensitivity to halogens, Bronsted and Lewis acids, halogenated compounds, and aromatic hydrocarbons, necessitating cautious handling during chemical modification attempts. Literature reports indicate the use of sulfuric acid for modifying the PEEK chain through sulfonation, albeit with the awareness of potential polymer degradation. Polyketones' high melting point, while advantageous for end-use applications requiring elevated temperature resistance, can pose challenges during the manufacturing of parts. To mitigate this, additives can be introduced to reduce the viscosity of polyketones, facilitating a more manageable and efficient production process. As a relatively recent thermoplastic innovation, polyketones are prominently employed in environments demanding resistance to high temperatures and corrosion. Their applications span various sectors, including automotive components like piston parts and bearings, structural elements in aerospace, chemical applications involving pumps and compressor valves, and electrical uses such as cables(49–56).

### 1.1.10 TPE (Thermoplastic Elastomers: Properties, Structures, and Applications)

In the realm of polymer science, Thermoplastic Elastomers (TPEs) stand out as a distinctive polymer class manifesting elastomeric characteristics despite lacking chemical cross-linkages. Originating from the 1950s, their utilization in commercial applications only materialized in the 1970s, coinciding with the advent of styrene copolymers. While traditional elastomers employ chemical cross-links to impede chain slippage during deformation, TPEs employ physical bonds arising from a micro-heterogeneous, 2-phase molecular structure. The intricate terminology surrounding these molecular systems becomes more comprehensible through illustrative examples. Physical cross-links within TPEs interconnect pliable molecules, establishing a network-like structure. These materials demonstrate processability at elevated temperatures and manifest elastomeric traits upon cooling. Notably, the transition from a thermoplastic to elastomeric state is entirely reversible, distinguishing TPEs from conventional elastomers. This characteristic facilitates repetitive processing and recycling, underscoring the sustainability aspect of these materials. Defined by a dual-phase structure comprising an elastomeric and a thermoplastic hard phase, TPEs must exhibit three fundamental properties for classification: the ability to extend at high elongation rates, thermoplastic processability at elevated temperatures, and minimal mechanical creep. The conceptualization of this structure becomes clearer through the examination of thermoplastic polyurethane elastomers, exemplifying the presence of "physical cross-links" in the form of hard segments. In the realm of thermoplastic polyurethane elastomers, segmented copolymers emerge from the reaction of pre-polymer polyol-containing diisocyanate and short-chain diol. The resulting soft segments, composed of pre-polymer polyol, coexist with polyurethane hard segments formed by diisocyanate and diol interaction. These hard segments exhibit ordered crystal structures, forming hydrogen bonds and acting as physical cross-links, which, despite stability at ambient temperatures, disintegrate during processing or solvent interaction, facilitating malleability and thin coating applications. Another paradigmatic example within the TPE domain is the A-B-A type tri-block copolymers, involving three dissimilar monomers and characterized by phase separation and cluster formation based on the incompatibility of blocks with differing monomers. Commercially, TPEs categorize into six main classes, encompassing styrene-based block copolymers, polyolefin blends, elastomer-based alloys, thermoplastic polyurethanes, thermoplastic copolyesters, and thermoplastic polyamides. Recent academic and industrial explorations into TPEs include interpenetrating networks and competitive polymer network structures, scrutinizing their chemical compositions and physical interactions. While TPEs offer advantages such as recyclability, thermoplastic processability, minimal compounding requirements, and ease of coloring, they are countered by high costs, limited compatibility with inexpensive additives like carbon black, and susceptibility to temperature and chemical influences. The production landscape of TPEs involves methods such as extrusion and injection molding, alongside thermal molding, thermal welding, and blow-molding techniques. Notably, mass production, particularly via injection molding, stands out for its rapid and cost-effective nature(57–59).

## 1.2 Exploring the Lifecycles of Ceramics: Production, Applications, and Waste Management

Ceramics, inherently inorganic and characterized by their hardness and brittleness, exist in either crystalline or amorphous states. Typically derived from a composite of clay, quartz, feldspar, and other minerals, or synthesized through specialized processes, ceramics find extensive utility across diverse industries and daily life. The production of ceramics involves selecting and preparing raw materials, forming the material into the desired shape, drying it, and then firing it in a kiln at a lower temperature (bisque firing). After bisque firing, glazing (if desired) and a second firing at a higher temperature take place. The ceramics may undergo a final firing, followed by quality control inspections. The finished ceramics are then packaged for distribution. Advanced ceramics may undergo additional processes like powder processing and precision machining. The specific production process can vary based on the type of ceramic being manufactured. The taxonomy of ceramics encompasses various types, each tailored for specific applications. Building ceramics, instrumental in construction, constitute one category. Electrical ceramics, prized for their electrical insulating or piezoelectric properties, find application in electronic devices and sensors. Art ceramics, crafts, and artworks also form a distinct category, while advanced ceramics are engineered for high-performance industrial applications, boasting attributes such as high temperature resistance, friction resistance, and chemical resilience. The distinguishing properties of ceramics encompass durability, hardness, electrical characteristics, thermal conductivity, and fracture resistance. Notably, ceramics exhibit a notable resistance to high temperatures, abrasion, and chemicals, surpassing metals and plastics in hardness. The expansive applications of ceramics traverse numerous domains: construction and decoration benefit from tiles, tiles, and ceramic coatings, while the electronics and electrical industry relies on ceramics for insulators, capacitors, and sensors. In the medical and biomedical field, ceramics find application in prosthetics and dental implants. The realm of arts and crafts embraces pottery and ceramic sculptures. Additionally, ceramics play a pivotal role in aerospace applications, featuring prominently in spacecraft and missile aerosol components. This versatility, stemming from the diverse properties of ceramics, positions them as indispensable materials across a multitude of industries and applications(60–65).

### 1.2.1 Waste Ceramics: Recycling, Sustainability, and Environmental Impact

Waste ceramics encompass material residues arising from construction, ceramics industry activities, and various industrial production processes. This category encompasses distinct types of waste, including:

-Building Ceramics: Constituting materials like tiles, ceramic plates, and porcelain utilized in construction projects.

-Industrial Production Wastes: Encompassing by-products, defective productions, and waste components generated during ceramic industry manufacturing processes.

-Porcelain Wastes: Arising predominantly from kiln processes, this category includes broken or faulty products during porcelain production.

-Ceramic Coating Wastes: Encompassing residues from the production or installation of ceramic coatings applied to surfaces like kitchen countertops, bathroom sinks, or flooring.

These diverse forms of waste ceramics often lend themselves to recycling or alternative applications through various processes. The management of waste ceramics carries the potential to contribute significantly to sustainable construction and production practices. Recycling entails repurposing waste ceramics for the manufacture of new materials or construction components, thereby curbing reliance on natural resources and mitigating landfill accumulation. Several methodologies can be employed in the recycling of waste ceramics, including fragmentation through grinding or milling for use as granular material, which frequently finds application in construction projects. Certain waste ceramics can undergo recycling processes to yield new ceramic products, thereby conserving raw materials in subsequent manufacturing endeavors. Moreover, the restoration of waste ceramic materials for reuse in construction or landscaping projects is a viable option. Alternatively, these materials can serve as aggregates in concrete or asphalt mixtures, presenting an environmentally conscious alternative. However, the recycling of waste ceramics is not devoid of technical and economic challenges, necessitating ongoing efforts and advancements in research and technology to enhance the efficiency of recycling processes. Continued exploration in this domain holds the potential to yield more effective solutions for the recycling and utilization of waste ceramics(66–71).

### 1.2.2 The Role of Waste Ceramics in Enhancing Polymer Composites

The amalgamation of waste ceramics with polymers emerges as a promising domain within materials science and engineering, presenting substantial prospects for sustainable material production. A primary merit of these applications lies in the synthesis of composite materials through the integration of waste ceramic components into polymer matrices. These composite materials seamlessly integrate the robustness inherent in ceramics with the pliancy characteristic of polymers, thereby facilitating the creation of more resilient and versatile materials across various industries. Notably, the formulation of building materials by incorporating waste ceramics into polymer matrices holds the potential to enhance the properties of construction materials. This transformative integration can concurrently bolster energy efficiency through heightened durability and reduced material weight. The consequential impact is particularly significant in the construction industry, where the adoption of such composite materials contributes to the optimization of structural properties and overall efficiency. The development of these applications signifies a strategic initiative aimed at mitigating the environmental footprint associated with waste ceramics, concurrently augmenting their recycling potential. The synergy between waste ceramics and polymers, therefore, not only addresses the sustainability imperative but also capitalizes on materials engineering advancements. Consequently, the amalgamation of waste ceramics with polymers emerges as a crucial focal point in both environmental sustainability and the expansive field of materials engineering, ushering in innovative avenues for research and application(66,67,72–75).

## 1.3. An Overview of Metal Materials and Their Varied Applications in Composites

### 1.3.1 Metals: Properties, Applications, and Industrial Significance

Metals, characterized by their inherent luster, conductivity, and malleability, represent a category of materials renowned for their proficiency in conducting electricity and effectively dissipating heat. Noteworthy for their high strength, magnetic attributes, and versatile applications across industries, metals undergo extraction from ores through mining and subsequent metallurgical processes, ultimately serving as foundational raw materials in various manufacturing endeavors. Alloy formation stands as a common practice to enhance the properties of metals, with examples including iron-carbon alloys like steel and copper-zinc alloys exemplified by brass. The deliberate amalgamation of metals into alloys refines their mechanical and thermal characteristics, broadening their utility across diverse industrial applications. Integral to the principles of natural resource conservation and environmental sustainability, metal recycling assumes paramount importance. Recognized as generally recyclable materials, metals undergo systematic processes to reclaim and reintegrate them into new production cycles. This practice not only mitigates the depletion of finite resources but also aligns with broader environmental imperatives, rendering metals essential contributors to the circular economy and sustainable material management(76–80).

### 1.3.2 Exploring the Versatility of Metal Matrix Composites

Metal Matrix Composites (MMCs) are composite materials formed by incorporating reinforcing materials into a metal matrix. These reinforcing elements frequently include ceramics, carbon fibers, or organic fibers. The widespread utilization of MMCs spans diverse sectors, including aviation, space exploration, automotive, electronics, and construction materials. The selection of these materials is primarily driven by their notable advantages, including high-temperature resistance, lightweight characteristics, and exceptional strength.

Various production methodologies contribute to the fabrication of MMCs, encompassing powder metallurgy, liquid phase injection, infiltration, and metal plating. Each method imparts distinct qualities to the resulting composite material, offering flexibility in tailoring MMCs to specific application requirements. MMC adoption addresses multifaceted industrial challenges, particularly excelling in applications demanding heightened performance attributes. The amalgamation of a resilient metal matrix with reinforcing elements lends MMCs the versatility to navigate and excel in environments characterized by elevated temperatures and stringent mechanical demands. This adaptability positions MMCs as instrumental materials in overcoming the evolving challenges encountered across diverse industrial landscapes(76,81–84).

### 1.3.3 Classifying Metal Matrix Composites: A Spectrum of Reinforcement Strategies

Aluminum Matrix Composites (AMC) constitute composite materials where an aluminum alloy serves as the matrix, commonly strengthened with materials like carbon fiber, silicon carbide, or alumina.

Titanium Matrix Composites (TMC) are composites where a titanium alloy acts as the matrix, typically reinforced with materials such as carbon fiber or alumina.

Magnesium Matrix Composites (MMC) are composite materials featuring a magnesium alloy as the matrix, frequently enhanced with materials like carbon fiber, boron carbide, or silicon carbide.

Steel Matrix Composites (SMC) employ steel alloys as the matrix, often fortified with materials such as ceramics, carbon fiber, or alumina.

Nickel Matrix Composites (NMC) involve composite materials where nickel alloys serve as the matrix, commonly strengthened with materials like ceramics or carbon fiber. These metal matrix composites find extensive use across diverse industrial applications, offering advantages such as lightweight composition, high strength, low density, and favorable thermal properties(81–83,85,86).

### 1.3.4 Metallurgical Influence: Unveiling the Impact of Metals on Polymer Composites

Incorporating a metal layer into polymer matrix composites represents a strategic approach to bolstering mechanical strength and enhancing various material properties. This additional metal layer contributes to improved heat transfer through heightened thermal conductivity, governs electromagnetic characteristics by increasing electrical conductivity, and fortifies wear resistance. Beyond these mechanical enhancements, the metal layer serves to augment corrosion resistance and introduce functional properties, making it adaptable to a diverse range of applications. The inherent high strength and durability of the metal layer exert a positive influence on the overall performance of polymer matrix composites. This synergistic integration of metal and polymer imparts a multifaceted improvement in material attributes, rendering the utilization of a metal layer in such composite materials highly popular. The amalgamation of these materials not only diversifies the functional capabilities but also aligns with the growing demand for advanced composite materials that can thrive in varied and demanding applications(76–79,82,85,86).

## 2. Findings and Conclusions

Research focused on the mechanical properties of thermoplastic composites infused with waste ceramics and metal aims to assess and enhance the material's performance characteristics. These composites exhibit the potential for superior mechanical durability and strength compared to traditional thermoplastics. The inclusion of ceramic and metal additives offers advantages by bolstering overall material durability, particularly in applications subject to heavy loads and harsh environmental conditions. The lightweight nature of metal fillers, coupled with the thermal and electrical conductivity properties of ceramic additives, expands the utility of the material across a broad spectrum of applications.

However, alongside these advantages, it's crucial to consider potential drawbacks, including increased production costs, reduced machinability, and the potential impact on abrasion properties due to metal fillings. These factors may influence the material's widespread availability and its commercial success in industrial applications.

The significance of incorporating waste ceramics aligns with sustainability goals, emphasizing the conservation of natural resources and the efficient utilization of waste. This approach represents a pivotal stride toward developing environmentally friendly material alternatives and fostering more sustainable industrial processes.

In conclusion, the investigation into the mechanical properties of thermoplastic composites with waste ceramic and metal additions contributes to the pursuit of innovative solutions in materials science and engineering. Such studies play a vital role in advancing the development of materials that are not only more durable and lightweight but also sustainable for future use in various industrial applications.

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