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Effect of Nanometal Oxide Loading Rates on Polymer–Nanometal Oxide Nanocomposites

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Abstract

Many industries, such as those in the fields of medicine, textiles, cosmetics, agriculture, optics, food packaging, optoelectronics, semiconductors, aerospace, building materials, and catalysis, utilize nanoparticles and nanocomposites in a variety of applications. A unique class of materials, polymeric nanocomposites outperform their microparticle counterparts by fusing organic polymers with inorganic nanoparticles. Consequently, they ought to advance the field of engineering applications. The presence of inorganic nanoparticles can significantly alter the properties of a polymer matrix. Titanium dioxide ($nTiO_2$) and zinc oxide (nZnO), two nanoparticle-reinforced polymer flexible composites, offer new design opportunities with exceptional mechanical and chemical capabilities. The mechanical, morphological, and thermal properties of polypropylene (PP) composite materials filled with $nTiO_2$ and nZnO were investigated in this study. Nanoparticles made up between 1 and 5 wt.% of the matrix. For improved surface adherence and fine dispersion, nanoparticles were coated with maleic anhydride grafted styrene ethylene butylene styrene (SEBS-g-MA), and silane, respectively, prior to melt mixing. To investigate the effects of modified and unmodified nanoparticles at various concentrations on the mechanical characteristics, morphological, and thermal properties, PP/nanoparticle nanocomposites were made using a twin-screw extruder and a heat press. Due to the stiff structure of nanoparticles, impact strength and elongation at break have decreased while all tensile parameters, such as yield strength and tensile strength, have increased. In spite of the fact that $nTiO_2$ has a higher hardness than nZnO, nanocomposites containing it showed more elongation than those containing the latter. The PP/$nTiO_2$ nanocomposite produced more than SEBS-g-MA due to the presence of silane. However, compared to nZnO nanocomposites, silane-modified $nTiO_2$ nanocomposites have better tensile properties. Reduced elongation at break is guaranteed in this case since the more refined structure of $nTiO_2$ with PP has been induced. The better compatibility of $nTiO_2$ with silane is probably to blame for this. Additionally, thermal analysis was done to figure out the melt temperature, crystallization temperature, and crystallinity level.

Keywords: Nanocomposites, polypropylene, nano-TiO_2, nano-ZnO, morphology, mechanical properties

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INTRODUCTION

The use of plastic materials is increasing because of their advantageous physical and chemical properties as well as technological development. These advantages make polymers popular for industrial applications. To provide products with more functional advantages than conventional polymers, reinforcements comprising glass fiber, graphite, or metal oxides are applied to polymer surfaces. Components made of metal, ceramic, and glass are starting to be replaced by these materials, which are also referred to as composites. They can be used in various industrial contexts [1, 2]. The use

of nanocomposite materials is widespread, and their production rates are increasing as nanotechnology develops. With a size of 100 nm, the nanocomposite was one of the phases of a multiphase material system. Nanocomposite materials have a high area-to-volume ratio because their filler particles are very small. Nanocomposites have many benefits including low weight, mechanical strength, resistance to chemical corrosion, and ease of production. The variety of applications of these resources has increased [3–5].

Several methods can be used to create nanocomposites. Solution blending, melt blending, and in situ polymerization are the most popular methods. The ideal method involves melting and mixing. Melt mixing is a step in the production of polymer nanocomposites. An extruder was initially used to melt the polymer and combine it with the required number of nanoparticles. Instead, the polymer and strengthening components were mixed dry, heated in a mixer, and sufficiently sheared to produce the required polymer nanocomposites. Melt blending provides numerous benefits over in situ polymerization and polymer solution mixing. Melt blending is environmentally beneficial because it does not require organic solvents. The possibility of using the melt blending process in industrial applications has led to its increasing popularity [6]. This approach is also more affordable than alternative approaches [7]. These products exhibit antibacterial, high mechanical, high ultraviolet (UV), and nonflammability properties [8, 9].

Polymers are commonly used in the fabrication of nanocomposite materials owing to their excellent properties, including flexible structures, simple manufacturing procedures, superior forms, and mechanical behaviors [4, 10, 11]. As a result of numerous studies on nanocomposites that focused on the polymer that would be used as the matrix phase, the quality of the polymer was noticeably improved, even when very small amounts of nanoparticles were added. Large-scale phase contact is possible owing to the high area-to-volume ratio of reinforcing nanoparticles and their nanoscale size [12]. Polymer-based nanocomposites are preferable to those composed of metal or ceramic matrices [13]. Polymer nanocomposites were fabricated using melt fiber spinning. Using this method, nanoparticles were integrated into the polymer matrix. Polymer matrix nanocomposites can provide composites with increased tensile strength and practical properties [4, 14, 15].

Polypropylene (PP) is one of the most important commercial polymers. It is commonly utilized in the production of containers, cars, cables, and ordinary plastics [16, 17]. It exhibited outstanding thermal and tensile properties at room temperature. Additionally, they exhibit a high chemical resistance rating [2, 18]. The textile industry uses polypropylene (PP) to provide functionality to textile products. It has what seems to be a flat waxy fiber structure. Polypropylene fibers are required to produce carpets, textiles, and technical textile products. They are preferred owing to their superior strength, economical manufacturing, and chemical resistance. The physical properties of polypropylene are listed in Table 1.

Fiber, which can be generated from a number of sources, is an essential fundamental material used in the textile industry. Alternative fibers are becoming increasingly popular, even though cotton fiber, which comes from natural sources, is still the most commonly used fiber in the industry. To create useful textile products, one of these fiber types, which is polymer-based, is reinforced with reinforcing components. The development of unique products and reduction of manufacturing problems are the main advantages of fiber-matrix polymer nanocomposites [19, 20].

Table 1. Polypropylene properties.

Properties	**Value**
Melting point (°C)	160–175
T_g (°C)	40
Density (gr/cm^3)	0.9
Degradation temperature (°C)	328–410

It is important to remember that nanoparticles impart special characteristics to composite materials, which are then improved and reinforced by reinforcing components to make composites more robust and useful. TiO_2, SiO_2, $CaCO_3$, and ZnO are only a few inorganic nanoparticles used to improve the mechanical properties of polymers [12, 21]. Although cost savings are the main advantage of utilizing inorganic fillers in polymer composites, other mechanical properties, such as rigidity, toughness, and dimensional stability can also be improved [22]. Numerous researchers in this field have combined ZnO with polymer composites to produce materials with excellent properties. Wacharawichanant et al. observed that the tensile strength did not increase considerably even when ZnO was added to a polypropylene composite [23]. Similar outcomes, including a decrease in the elastic modulus, yield strength, and tensile strength of the composite, were observed in related comprehensive tests conducted by other researchers [24]. Similar results were obtained when $CaCO_3$ and other inorganic fillers were added to polypropylene composites, producing low values of tensile strength [25]. Because TiO_2 is non-toxic, it has garnered a lot of interest from inorganic filler manufacturers. Additional advantages of TiO_2 include its high hardness, chemical inertness, affordability, and ability to filter UV rays. Several researchers have investigated the use of TiO_2 with PP to improve the physical and mechanical properties of the composites. As a result, the tensile strength of the PP composite was greatly increased when TiO_2 was added [26–30].

Polymers reinforced with nanometal oxides are becoming increasingly popular owing to their improved mechanical strength, design flexibility, and improved chemical, electrical, and optical properties [31]. Agglomeration of the nanoparticles, on the other hand, may degrade the properties of the nanocomposites. To resolve this issue, dispersants and coupling agents have been used [12]. Another difficulty that is regularly encountered is the decrease in the stiffness of the inorganic material, which causes the impact strength to decrease. Researchers have used elastomeric natural materials to increase the durability of composites [32]. This study examined the mechanical, morphological, and thermal properties of polypropylene reinforced with titan dioxide and zinc oxide at the nanoscale level. Improved tensile properties were achieved using silane and SEBS-g-MA for improved dispersion and surface adhesion between the metal oxide and the matrix.

EXPERIMENTAL

Ingredients & Production of the Nanoparticles

PP was purchased in pellet form from Lotte Chemical Titan Malaysia, with a melt flow index of 14 g/min and a density of 0.900g/cm^3. The Chinese Nabond Company employed ZnO and TiO_2 as nanomaterials. For better surface adhesion and dispersion, the nanoparticles were coated with vinyltrimethoxysilane (VTMS, Aldrich) and SEBS-g-MA (FG1901X, Kraton, Shell Company). To coat the nanometal oxide particles, they first utilized SEBS-g-MA and subsequently silane. It was anticipated that the coupling agent function of SEBS-g-MA would work better when coated onto powders when used as a compatibilizer. The silane coating resulted in more evenly distributed SEBS-g-MA-coated particles in the polymer matrix. Coating was performed by combining SEBS-g-MA with nanoparticles dissolved in toluene over a period of 48 h at 25°C. The mixture was dried for eight hours at 50 °C, and the SEBS-g-MA-coated nanoparticles were ground. Pure alcohol (96%), distilled water (4%), and silane (1%) were combined to create coating solutions. Nanoparticles coated with SEBS-g-MA were gradually added to the mixture after three hours of mixing. The mixture was ground after an eight-hour 50°C.

Two types of compatibilizers (SEBS-g-MA and silane) and a predetermined amount of PP, as well as varying amounts of nanoparticles (1, 3, and 5 wt.%) and a fixed amount of 3 wt.% nanoparticles were used to form the nanocomposite samples. The following code applies to both coated and uncoated nanocomposites: for uncoated, PP/1 wt.% nTiO_2 (marked as PP/1UnTiO_2), PP/3UnTiO_2, PP/5UnTiO_2 and PP/1UnZnO, PP/3UnZnO, PP/5UnZnO, and for coated, PP/silane-coated 1 wt.% nTiO_2 (indicated as PP/1SnTiO_2), PP/3SnTiO_2, PP/5SnTiO_2 and PP/SEBS-g-MA-coated 1 wt.% nZnO (designated as PP/1SEnZnO), PP/3SEnZnO, and PP/5SEnZnO. PP and nanoparticles were placed in a 44 L/D twin-screw extruder, designated as ZE-25A UTX, manufactured by Krauss Maffei Berstorff GmbH in

Germany. The screw was rotated at a speed of 100 rpm while operating in the temperature range of 180–220°C. Extruded strands are ground into tiny pellets, and the resulting pellets are then used in a hot press machine to produce thin plates.

Characterizations

Transmission electron microscopy (TEM) and scanning electron microscopy (SEM) were used to study the fracture surfaces and nanoparticle dispersions, respectively. Scanning electron microscopy (SEM, JSM-6360LV, JEOL, Tokyo, Japan) was used to analyze the fracture surfaces of the nanocomposites. The samples were coated with gold before imaging. Transmission electron microscopy (TEM, JEM-2100F, JEOL) was used to assess the dispersion of PP and nanoparticles.

Tensile tests were performed using a Shimadzu Universal Testing Machine (AG-1, Japan). The samples were 2 mm thick, 10 mm wide, and 50 mm gauge length. At a crosshead speed of 10 mm/min, the yield strength, tensile strength, tensile modulus, and elongation at break were examined. The Izod impact test was performed on a Zwick impact test machine with notched specimens and a 5.4 J pendulum hammer. In compliance with the ASTM-D 638-03 standard, five repeat tests were conducted to obtain an average value for each sample in all experiments [33].

Differential Scanning Calorimetry

A nitrogen environment was used to study the melting and crystallization behaviors using differential scanning calorimetry (DSC; Perkin Elmer DSC-7). The samples (5-8 mg) were heated from 40 to 180 °C at a rate of 10 °C/min for 5 min and then cooled to 40 °C at a rate of 10 °C/min for 5 min. The thermal history of the samples was removed using a second heating cycle. We measured the crystallization degree (X_c), crystallization temperature (T_c), and melting temperature (T_m). The fusion enthalpy of the 100% crystalline phase of PP was 209 J/g to calculate the degree of crystallization of the blends [34].

A DISCUSSION ON THE FINAL RESULTS

Mechanical Characteristics

Metal oxide nanoparticles have been used to enhance the mechanical characteristics of polymer matrices [35]. The variations in the yield and tensile strengths of PP, PP/uncoated $nTiO_2$, PP/uncoated nZnO, PP/silane-coated $nTiO_2$, PP/silane-coated nZnO, PP/SEBS-g-MA-coated $nTiO_2$, and PP/SEBS-g-MA-coated nZnO are shown in Figures 1(a) and (b). It can be seen that the yield strength and tensile strength increased when the nanometal oxide content was increased up to 3 wt.% (yield strength increased by 16.9% and tensile strength increased by 20% for PP/$UnTiO_2$ nanocomposites compared to PP, and the yield strength increased by 6% and tensile strength increased by 12% for PP/UnZnO nanocomposites), and then decreased by 5 wt.%. In this scenario, neither the yield strength nor the tensile strength of the material is affected by any portion of the external load because the agglomerated nanoparticles are swiftly separated from the polymer. The results obtained by Zaman et al. were validated [36]. The modification of PP/$nTiO_2$ or PP/nZnO nanocomposites to strengthen the interfacial interaction between PP and nanometal oxide particles was made possible by silane and SEBS-g-MA. The introduction of silane in the PP/$nTiO_2$ or PP/nZnO nanocomposites significantly improved the interfacial interaction between the nanometal oxide and PP compared to the PP/$UnTiO_2$ or PP/nZnO nanocomposites. At a nanometal oxide concentration of 3 wt.%, the highest yield strength and tensile strength of the PP/$SnTiO_2$ and PP/SnZnO nanocomposite, which were approximately 32%, 31%, 20%, and 19% greater than those of the PP matrix, were 28.9 MPa and 26.3 MPa, respectively. PP/$SnTiO_2$ exhibited the highest yield and tensile strength, followed by PP/SnZnO came in second. The strength of the compatibilized system increased because of the stronger distribution that the compatibilizer generates and enhances solid-state adhesion, which can transmit more stress from the matrix to the dispersion phase. PP/$SEnTiO_2$ or PP/SEnZnO have a lower strength while having the same quantity of nanometal oxide as PP/$SnTiO_2$ or PP/SnZnO because they also contain the elastomeric phase of SEBS-g-MA.

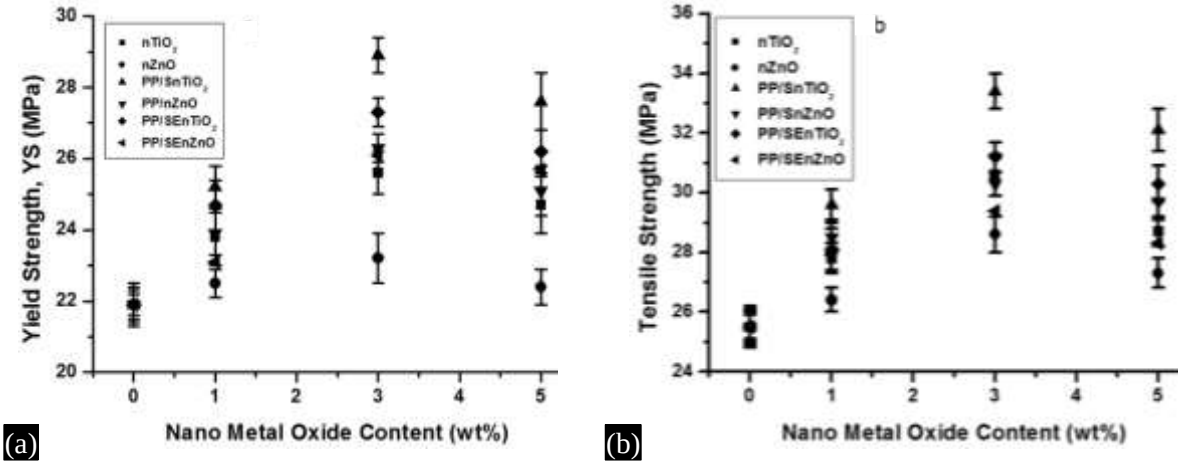

Figure 1. Tensile properties of PP nanocomposites reinforced with nanoscale titanium dioxide and nanoscale zinc oxide, (a) yield strength, and (b) tensile strength.

Figures 2(a) and (b) show the nanocomposites' tensile modulus and elongation at break as a function of the nanometal oxide content. With the addition of nanometal oxides, the tensile modulus increased consistently, while the elongation at break decreased gradually. By developing the modulus, stress can be efficiently transferred from the PP to the nanometal oxide particles. The fact that elongation decreased when nanometal oxide was added, on the other hand, suggests that the substance might interfere with or deform PP. Mechanical restraint of the PP and personal contact were the causes of this interference. When there was 5% nanometal oxide content, silane significantly increased the tensile modulus. The silane-coated nanometal oxide particles were finely dispersed, and the PP and nanometal oxide particles had strong adhesion, which will be discussed in more detail later. As a result, the tensile modulus increased. The SEBS-g-MA nanocomposites, on the other hand, showed strong tensile moduli with a nanometal oxide level of 5% by weight. The coating of nZnO particles on SEBS-g-MA was not distributed as finely as the $nTiO_2$ particles, as shown by the results of the tensile test. Materials with higher yield strengths, tensile strengths, and tensile moduli have been developed using $nTiO_2$ because of its rigid structure and higher hardness than those of nZnO. Instead, it was anticipated that PP/$nTiO_2$ nanocomposites would exhibit reduced elongation when compared to nZnO-reinforced nanocomposites; instead, the opposite was demonstrated to be true to a greater than 1 wt.% degree. This suggests that $nTiO_2$, silane, and SEBS-g-MA may interact with each other more efficiently than nZnO.

The impact features observed during the impact tests are shown in Figure 2(c). Nanometal oxide was added, but the harder particles resulted in a reduction in the impact strength. However, when PP/$SnTiO_2$ and PP/$SEnTiO_2$, as well as PP/SnZnO and PP/SEnZnO, were compared with the nanocomposites that had silane or SEBS-g-MA, the impact strength was increased. The addition of silane produces the nanocomposite toughness through the improved impact strength and PP's molecular flexibility. With an increase in the nanometal oxide content, the impact strength decreased because of the presence of agglomerates, which will be discussed later. As the amount of nanometal oxide increased, agglomerates developed and the interfacial nanometal oxide-PP adhesion decreased because SEBS-g-MA did not provide an excellent dispersion as it did in silane. As a result, despite the presence of the elastomer phase, inadequate impact strength has been reported in PP/$SEnTiO_2$ and PP/SEnZnO nanocomposites. It is well known that each agglomeration causes cracking and reduces its impact strength.

Surface Morphology and Particle Dispersion

The homogeneity of different morphologies, domain sizes, and shapes, as well as their relationship to mechanical properties, are among the most important factors in determining the degree of dispersion of interactions between the two phases [37]. TEM images of the PP/$nTiO_2$ nanocomposites formed with 3 wt.% $nTiO_2$ (designated as PP/3UnTiO$_2$), 3 wt.% $nTiO_2$ coated with PP/silane (designated as PP/3SnTiO$_2$), or 3 wt.% $nTiO_2$ coated with PP/SEBS-g-MA are shown in Figure 3(a-c).

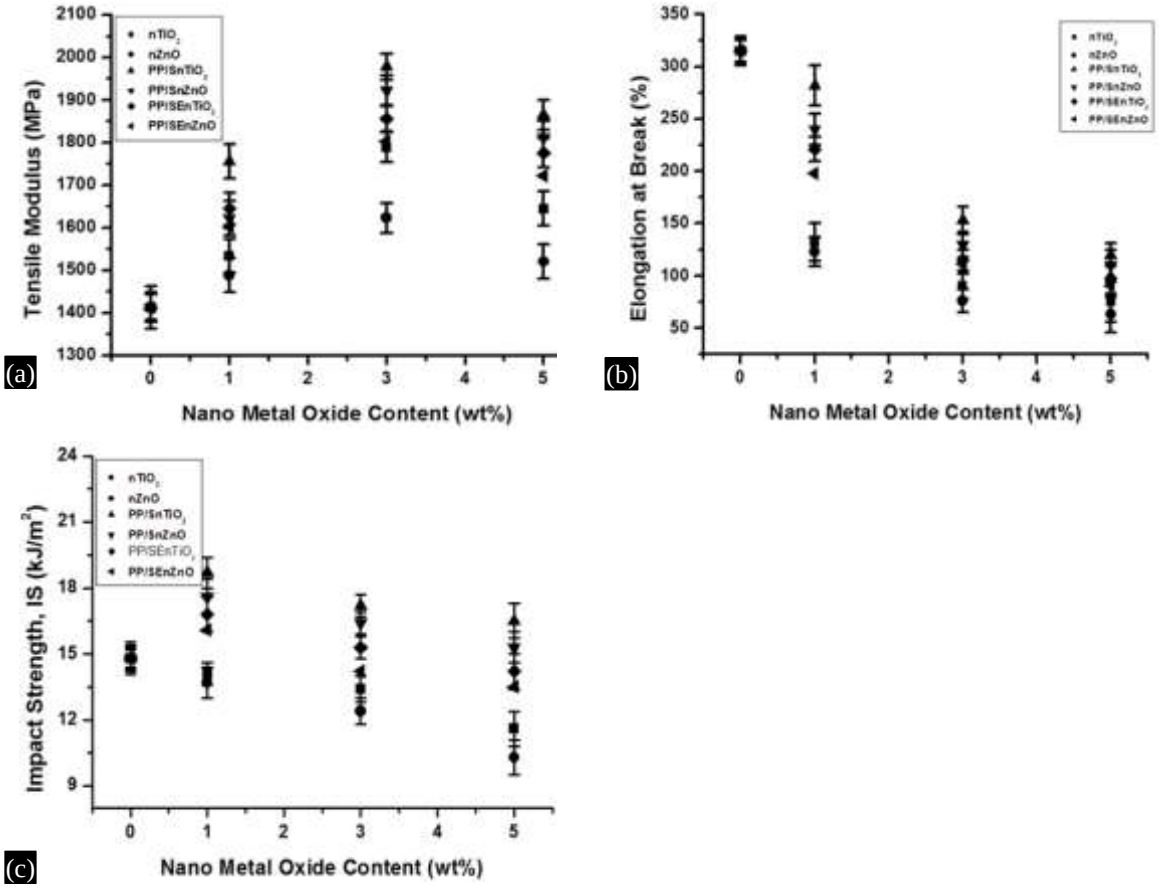

Figure 2. Tensile and impact properties of PP nanocomposites reinforced with $nTiO_2$ and nZnO, such as (a) tensile modulus, (b) elongation at break, and (c) impact strength.

The significantly larger $nTiO_2$ particles in Figure 3(a) are not intercalated and most likely form a "micro composite" structure because there is no silane or SEBS-g-MA. The PP continued across the remaining space, and the $nTiO_2$ tactoids were visible in black. However, the poor dispersion of some $nTiO_2$ particles can be represented by specific black forms. Figure 3(c) shows a lower number of $nTiO_2$ particles compared to Figure 3(a), and they have been blended into lighter parts. Silane, which functions as a compatibilizer and intercalator between PP and $nTiO_2$ (Figure 3b), might be added to obtain a better dispersion. The PP/3SnTiO$_2$ systems demonstrate better and more uniform $nTiO_2$ dispersion in the PP matrix because the black shape of silane is less obvious than in the PP/3SEnTiO$_2$ system. Figures 3(d)–3(f) show the TEM images of the nanocomposites PP/3UnZnO, PP/3SnZnO, and PP/3SEnZnO. The very large nZnO particles in Figure 3(d), which are not intercalated, show a strong dispersion between PP and nZnO. The TEM photomicrographs of PP/3SnZnO shown in Figure 3(e) show that the nZnO particles were evenly distributed throughout the matrix and were almost completely immersed in it. This ensured both the compatibility of the two materials and the strong bonds produced between $nTiO_2$ and PP. However, when the SEBS-g-MA coating was applied, the dispersion of nZnO particles was less than that shown in Figure 3(e) (Figure 3(f)), even though some nanoparticles were split into lighter parts during the mixing process. In addition, the silane coating on the nZnO particles enhanced the surface adhesion and fine dispersion when compared to the silane coating on the $nTiO_2$ particles.

The fracture surfaces of the nanocomposites are shown in the SEM photomicrographs in Figure 4. Figures 4(a) and (d) illustrate the random placement of uncoated $nTiO_2$ or nZnO with nanocomposites in the PP matrix. Several agglomerates larger than 1 m in size were exposed above the fracture surface. The PP to PP/3UnTiO$_2$ nanocomposite has large particles because there is no functional polymer present, and the interfaces seem to be individually wet and/or weak to the adhesion of the components.

This illustrates the high impact resistance and poor tensile properties of the nanocomposites discussed above. Figure 4(b) and (e) depict the nanocomposites made of $3SnTiO_2$ and 3SnZnO particles, respectively. These nanoparticles were spread more evenly across the PP matrix and were efficiently dispersed without aggregation. This demonstrates that soaking the nanoparticles has a major impact on the connection, adhesion, and direct contact between the TPE and $nTiO_2$/nZnO. The $3SnTiO_2$ particles were more equally dispersed in the PP matrix than the 3SnZnO particles were. This lends credence to the advantages of the improved mechanical properties of the nanocomposites.

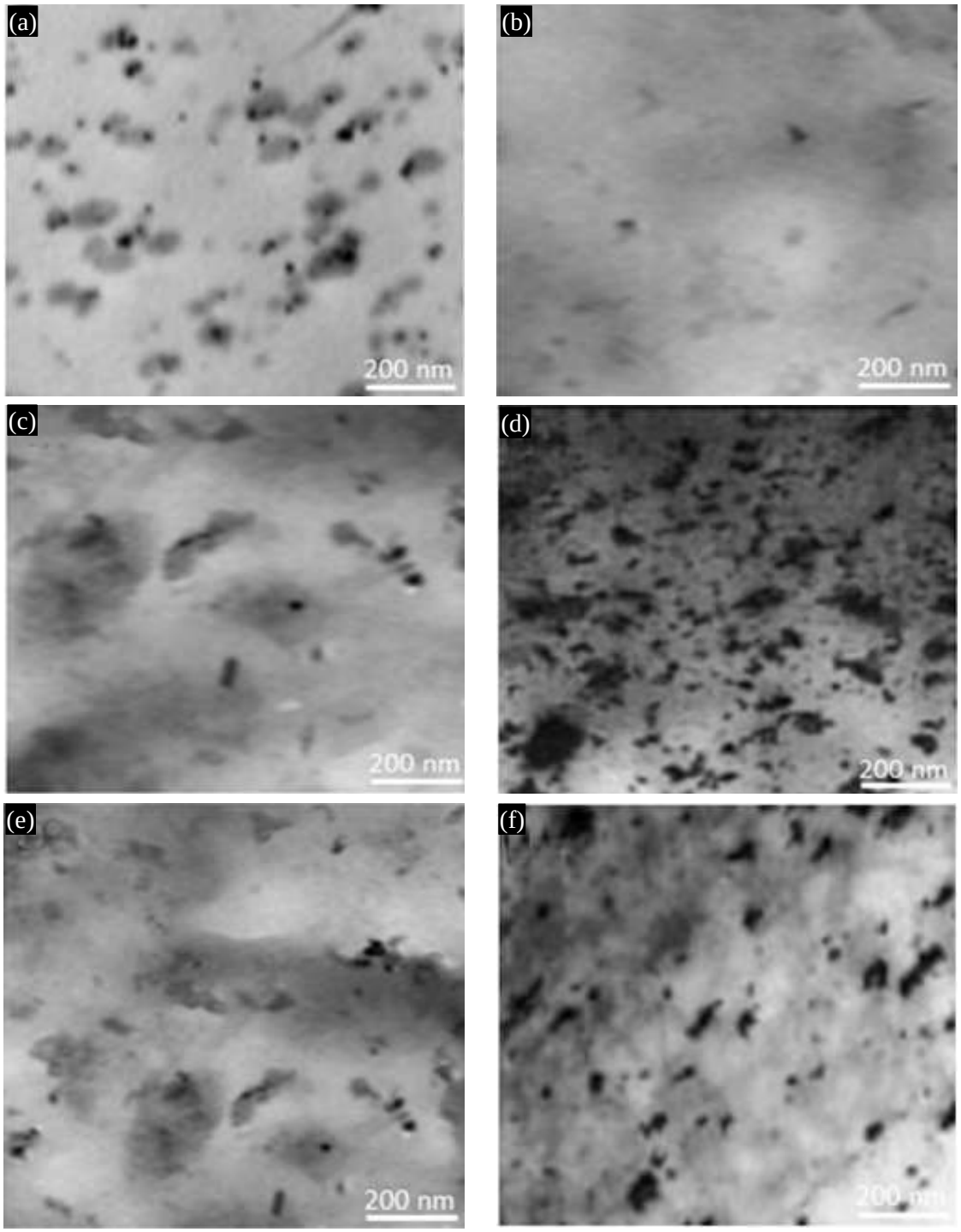

Figure 3. TEM images of (a) PP/$3UnTiO_2$, (b) PP/$3SnTiO_2$, (c) PP/$3SEnTiO_2$, (d) PP/3UnZnO, (e) PP/3SnZnO, and (f) PP/3SEnZnO.

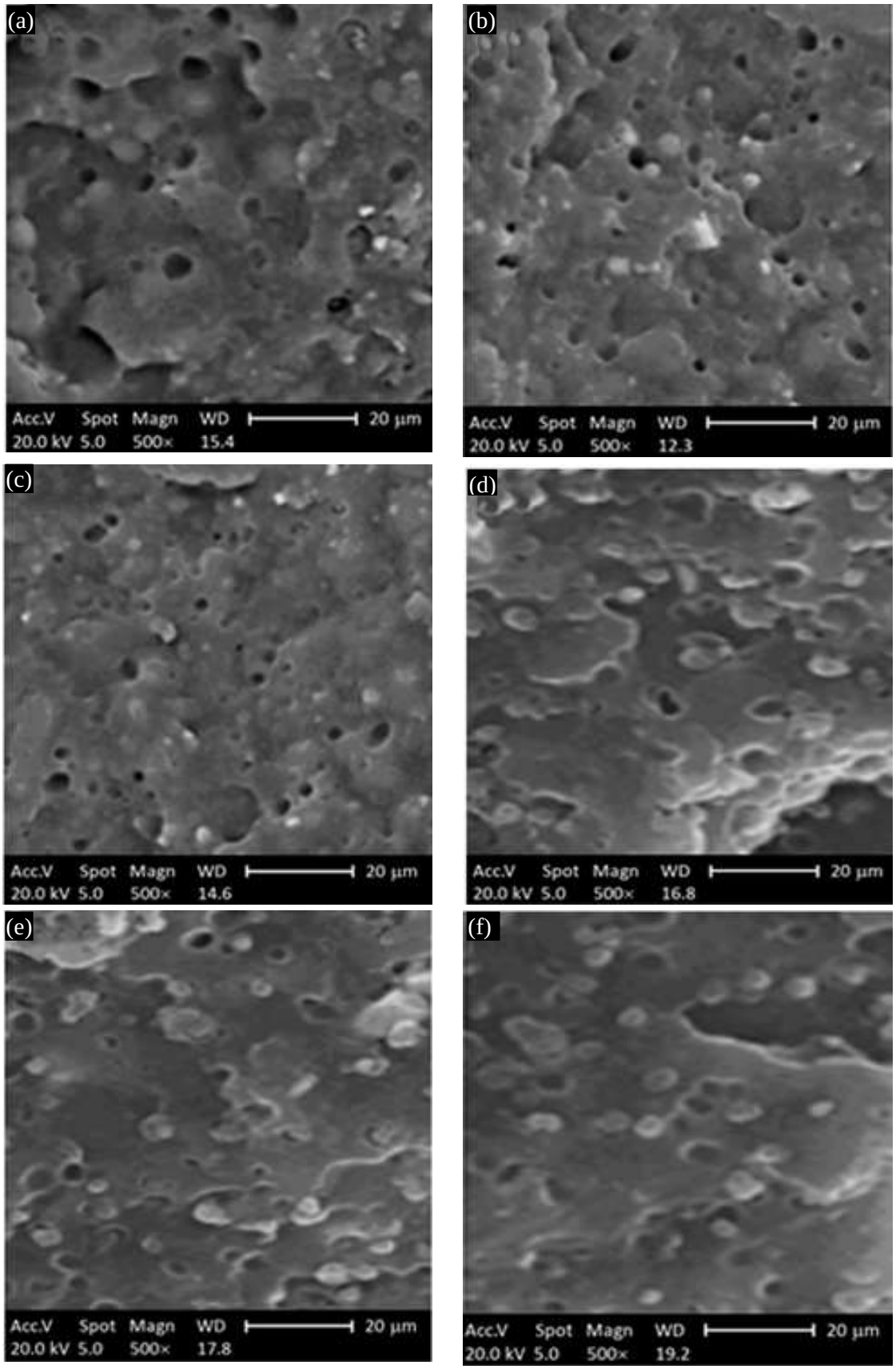

Figure 4. SEM pictures of (a) PP/3UnTiO$_2$, (b) PP/3SnTiO$_2$, (c) PP/3SEnTiO$_2$, (d) PP/3UnZnO, (e) PP/3SnZnO, and (f) PP/3SEnZnO.

Table 2. Thermal properties of nanocomposites.

Mixture	T_m (°C)	T_c (°C)	Enthalpy (J/g)	X_c (%)
Pure PP	166.5	126.7	87.3	42.4
PP/1 $nTiO_2$	165.7	124.9	84.5	41.3
PP/3 $nTiO_2$	166.3	126.5	83.6	40.7
PP/5 $nTiO_2$	166.5	127.3	85.2	41.8
PP/1 nZnO	166.6	125.4	69.5	33.5
PP/3 nZnO	165.8	125.7	67.5	31.6
PP/5 nZnO	165.8	125.4	68.2	31.9

Figures 4(c) and (f) depict the morphological structures of the nanocomposites, including the 3SEnTiO_2 and 3SEnZnO particles. The PP/3SEnTiO_2 and PP/3SEnZnO systems contain larger parts and smaller average particle sizes than the PP/3UnTiO_2 and PP/3UnZnO systems. By comparison to 3UnTiO_2/3UnZnO, 3SEnTiO_2/3SEnZnO and SEBS-g-MA were more compatible, as shown by this. However, nanoparticle agglomerates formed in some regions of the PP matrix decreased the tensile characteristics of the PP/3SEnTiO_2 and 3SEnZnO nanocomposites. The superior surface adhesion and fine structure of the 3SnTiO_2 particles to PP, as compared to the 3SnZnO particles, confirmed the superior tensile properties of the PP/3SnTiO_2 nanocomposite.

Thermal Characteristics

The DSC results for the composites are listed in Table 2. The melt temperature (T_m) and crystallization temperature (T_c) were unaffected by the addition of nTiO_2 and nZnO. On the other hand, the addition of nZnO reduced the level of crystallization more than the addition of nTiO_2, indicating that the nTiO_2 particles had no impact on the stability of PP. The physical hindrance effect of the nano-ZnO on the molecular chains and the retarding effect on the PP crystals were more pronounced in the PP/nZnO composites. The increased physical compatibility of nTiO_2 with SEBS-g-MA and finer nanoparticle dispersions are likely responsible for this outcome. Numerous studies have been conducted on the effect of nanoparticles on the degree of crystallization. Different experimental findings led to different results, and some studies recognized these particles as nucleating agents [38, 39]. For instance, as the amount of nanofiller increased in PP with nano-$CaCO_3$ filler, the crystallinity remained unaltered [38]. However, further studies on clay/PP composites revealed either an increase or decrease in crystallinity [39, 40]. The findings of this experiment were also supported by Chandramaouleeswaran et al. [16], who reported a decrease in the crystallinity of PP/nano-ZnO composites. Most research on nano-titan dioxide reinforced composites [41, 42] concluded that nTiO_2 had no substantial effect on the degree of crystallinity or function as a nucleating agent [24, 43].

CONCLUSIONS

Metal oxides enhance the mechanical properties; however, each metal oxide behaves differently based on its physical, mechanical, and chemical properties. To prepare the PP/nanometal oxide nanocomposites, a melt mixing process under the supervision of a hot press machine was used. In this study, the inclusion of two nanometal oxides, nTiO_2 and nZnO, improved the mechanical properties of the polypropylene composites. In this study, the effects of surface-modified nanometal oxide particles were examined along with the mechanical, morphological, and thermal properties of PP/nanometal oxide nanocomposites. Owing to the inclusion of metal oxide nanoparticles, PP/nanometal oxide nanocomposites exhibit stronger tensile properties than the pure PP matrix; however, the impact strength and elongation at break were reduced. The addition of silane or SEBS-g-MA-coated metal oxide nanoparticles significantly changed the tensile properties of PP, such as yield strength, tensile strength, and tensile modulus, but decreased the impact strength and elongation. Stronger surface bonding was provided by SEBS-g-MA-coated metal oxide nanoparticles in addition to fine dispersion with silane-coated nanometal oxide. Materials with greater yield strength, tensile strength, and tensile modulus have been developed using nTiO_2 because of its rigid structure and

higher hardness than that of nZnO. However, it was anticipated that PP/nTiO_2 nanocomposites would exhibit less elongation than nZnO-reinforced nanocomposites; however, the opposite was demonstrated to be true to a greater than 1 wt.% degree. As a result, it can be shown that nTiO_2 and silane were more compatible than nZnO. In addition, the presence of nanometal oxide agglomerates in particular areas of PP reduced the tensile properties of the PP/nZnO nanocomposites. The tensile characteristics and crystallinity of the PP/nZnO composites were also decreased by the nZnO agglomerates that developed in some locations in the matrix.

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