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Microwave welding with SiCNW/PMMA nanocomposite thin films: enhanced joint strength and performance

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Abstract

Most previously reported susceptors for microwave welding are in powder form. In this study, a thin-film susceptor was employed due to its uniform heating rate and ease of handling. Silicon carbide nanowhisker (SiCNW) were incorporated into a poly(methyl methacrylate) (PMMA) matrix to create a nanocomposite thin film, which served as the susceptor. The microwave welding process involved three straightforward steps: fabrication of the PMMA/SiCNW nanocomposite thin film, application of the nanocomposite film to the target area, and subsequent microwave heating. Upon cooling, a robust microwave-welded joint was formed. The mechanical properties and microstructure of the welded joints were characterized using single-lap shear tests, three-point bending tests, and scanning electron microscopy. Results demonstrated that the shear strength and elastic modulus of the welded joints were optimized with increased heating time and SiCNW filler loading. This optimization is attributed to the formation of a SiCNW-filled polypropylene (PP) nanocomposite layer of increasing thickness at the welded joint interface. However, the incorporation of SiCNW also constrained the mobility of the PP chains, reducing the joint's flexibility. Furthermore, the welded joint formed with the PMMA/SiCNW nanocomposite thin-film susceptor exhibited an 18.82% improvement in shear strength compared to joints formed with a powdered SiCNW susceptor. This study not only demonstrates the potential of PMMA/SiCNW nanocomposite thin films as efficient susceptors

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for microwave welding but also paves the way for developing high-performance polymer-based composite joints with improved mechanical properties for applications in the automotive, aerospace, and construction industries.

Keywords: microwave welding, silicon carbide, nanowhisker, nanocomposite thin film, susceptor

1. Introduction

Microwave susceptors are a class of high-loss materials capable of rapid heating through microwave irradiation, even at ambient temperatures [1]. When exposed to microwaves, these susceptors absorb electromagnetic energy and convert it into thermal energy, resulting in efficient microwave heating. However, microwave heating is not effective for most materials. The extent of microwave interaction with a material is primarily determined by its magnetic and electric properties and the penetration depth of the microwaves. Materials can be categorized as microwave reflectors, microwave-transparent materials, or microwave susceptors, based on their penetration depth and their interaction with microwave radiation [2]. Microwave reflectors, such as metals, have extremely low penetration depths (on the order of micrometers), allowing microwaves to interact only with the material's surface layer, reflecting most of the radiation. In contrast, microwave-transparent materials possess a very high penetration depth (greater than 10 m), enabling microwaves to pass through without significant interaction. Examples of microwave-transparent materials include polymers, quartz, glass, and Teflon. Microwave susceptors occupy an intermediate range, with penetration depths typically in the order of centimeters. These materials can efficiently absorb microwave radiation and convert it into thermal energy, depending on their specific electrical and magnetic properties [3–6].

Microwave heating is recognized as a rapid heating method because electromagnetic energy is directly transferred at the molecular level within the microwave susceptor [7]. Unlike conventional heating, which relies on an external heating element to transfer heat from the surface to the core of the material through conduction or convection, microwave heating generates heat volumetrically throughout the entire material. This unique mechanism minimizes temperature gradients across the material and enhances uniform heating [8]. Due to its volumetric heating principle, microwave heating provides several advantages, including reduced processing time, lower power consumption, and accelerated diffusion rates [8]. Additionally, microwave heating offers a controllable heating rate, a high degree of safety, and is environmentally friendly, making it a highly efficient and sustainable option for various applications [9].

Carbon materials (such as graphite and carbon nanotubes (CNTs)), metal oxides (such as Fe_3O_4 and NiO), and silicon carbide (SiC) are commonly used susceptors in microwave processing [10]. These materials can be utilized in various shapes and forms. Among these, SiC is distinguished by its high dielectric properties—including both dielectric constant and dielectric loss—and its exceptional microwave absorption capabilities. As a result, SiC is one of the most extensively used susceptors in microwave applications. SiC is an inorganic ceramic material composed of covalently bonded silicon and carbon atoms in a tetrahedral structure. It possesses several outstanding properties, such as non-toxicity, high thermal, chemical, and oxidation resistance, and the ability to retain its mechanical integrity in harsh environments up to 1600 °C [10, 11]. Due to these superior characteristics, SiC is often preferred over carbon and oxide materials, which may suffer from issues such as carbon migration, toxicity, and oxidation during microwave processing [12]. Furthermore, in a comparative study of microwave heating capabilities among various susceptor materials, Patel *et al* demonstrated that SiC exhibited a higher microwave heating rate than graphite and pulverized carbon. This enhanced heating performance of SiC is attributed to its strong dipole interactions in an oscillating electric field, which contribute to a higher dielectric loss factor [13].

Previous studies have demonstrated that SiC can serve as an effective susceptor in a range of microwave-assisted material processing techniques, including material synthesis [11, 14], sintering [15, 16], casting [17], and joining or welding [18, 19]. Microwave welding, specifically, is a joining method that utilizes microwave irradiation and a susceptor to fuse two or more individual components into a larger, more complex structure. In addition to the inherent benefits of microwave heating, microwave welding offers advantages such as ease of disassembly, a tunable heating rate, and versatility across various geometries. As a result, considerable efforts have been directed toward exploring microwave welding for metallic components. For example, Kumar *et al* successfully developed a microwave-welded joint between SS304 and SS316 metal pieces using SS316 powder as a filler material. Their results indicated that a homogeneous welded joint was achieved, with optimized microhardness attributed to the formation of carbides at the joining interface [20]. However, microwave welding of thermoplastics has been scarcely reported. This scarcity is largely due to the microwave transparency of most thermoplastic materials, which prevents a significant temperature rise under microwave irradiation. To address this challenge, a susceptor material is introduced at the joining interface to raise the temperature of the parts being joined to a molten state, allowing for their coalescence into a single structure upon solidification.

Nanomaterials have recently garnered significant interest from researchers due to their relatively high specific surface area and a greater number of active sites compared to their macro-sized counterparts. In the context of microwave welding, the size of the susceptor material also plays a crucial role in determining the properties of the welded joint. For instance, Sun *et al* investigated the microwave welding of polypropylene (PP) substrates using graphite susceptors of varying particle sizes [21]. In their study, they prepared two types of graphite powders by ball-milling the as-received graphite powder (250–850 μm) to achieve a finer particle size of 90 μm. The results showed that when the ball-milled graphite powder was used as the susceptor, there was a 1.5-fold increase in the tensile strength of the microwave-welded joint compared to the joint formed using the as-received graphite powder. This finding indicates that the strength of microwave-welded joints can be effectively optimized by reducing the particle size of the susceptor.

Historically, most researchers have used carbonaceous materials, such as pure powder or composite powder, as susceptors for microwave welding. For example, Wu *et al* investigated the welding of PP using a CNT/PP composite powder as a susceptor under microwave heating [22], while Sun *et al* reported microwave welding of PP using single-walled CNTs (SWCNTs) alone as a susceptor [23]. However, achieving a consistent thickness of powdered susceptors on substrates is challenging. The non-uniform thickness can significantly affect the amount of susceptor present, as well as its microwave absorption and heating rates. Consequently, areas with a higher concentration of the susceptor may overheat, resulting in defects in the welded joint, while regions with a lower concentration may not be properly welded. Xie *et al* explored the joining of polyethylene (PE) using super-aligned CNT (SACNT) films as susceptors under microwave irradiation [24]. They found that, despite prolonged sonication of CNT powder, the temperature distribution along the PE substrates remained uneven. This issue arose because the CNT bundles were strongly entangled and agglomerated, limiting their effective surface area for microwave absorption. As a result, the CNT coatings on the substrates could not be heated uniformly, leading to localized overheating, degradation, and the occurrence of fire flashes, sparks, and smoke. This problem was mitigated when SACNT films were used as susceptors for microwave welding of PE substrates. However, synthesizing SACNT films is both difficult and expensive, and CNTs pose health risks, including carcinogenicity and lung irritation with prolonged exposure [12]. Given these challenges, it is hypothesized that composite thin films offer advantages over powder-based susceptors, particularly in ensuring uniformity and homogeneity. Moreover, compared to powdered susceptors, composite thin films are more portable and easier to handle. To date, no studies have been reported on the use of SiC nanomaterial-based nanocomposite thin films as susceptors for microwave welding of thermoplastics. Therefore, this study focuses on the preparation of a SiC nanocomposite thin film, which is subsequently employed as a susceptor for microwave welding.

Previous studies have demonstrated that a thicker molten layer can enhance the joint strength of microwave-welded joints [25]. Among the critical processing parameters, microwave heating time significantly impacts the microwave absorption performance and the amount of heat generated by the susceptor, which, in turn, influences the thickness of the molten layer formed. Additionally, the loading of the susceptor plays a crucial role in determining the heating rate; a higher susceptor loading increases energy absorption and heat emission to the surrounding thermoplastic, resulting in a thicker molten layer and improved joint strength. In this study, PP was used as the thermoplastic substrate, while a silicon carbide nanowhiskers/poly(methyl methacrylate) (PMMA/SiCNWs) nanocomposite thin film served as the susceptor for microwave welding. The effects of microwave heating time and the filler loading of SiCNW in the PMMA/SiCNW nanocomposite thin film on the cross-sectional microstructure and mechanical properties of the welded joint were systematically investigated. Furthermore, this study proposed a formation mechanism for SiCNW-reinforced PP at the joint interface.

2. Materials and methods

2.1. Materials

PP pellets (Titanpro 6331, Lotte Chemical Titan (M) Sdn Bhd, Malaysia), PMMA pellets (LG Chemical, South Korea), SiCNW with 99% purity and a particle size of 100–250 nm (Nanostructured & Amorphous Materials Inc., USA), and acetone (HmbG Chemical, Germany) were used as received, without any further purification.

2.2. Fabrication of PP substrates

PP substrates were fabricated from PP pellets using a heat press machine (GoTech, Taiwan) and a customized cutter. Initially, the required amount of PP pellets was weighed and placed into a mold cavity with a thickness of 1.6 mm. The mold was then positioned between two flat metal plates and preheated in the heating compartment of the hot press machine for 6 min, followed by hot pressing under pressure for an additional 3 min. After pressing, the mold assembly was transferred to the cooling compartment and cooled for 3 min, yielding a PP sheet.

To produce PP substrates for microwave welding, a customized cutter, designed according to ASTM D3163 and ASTM D790 specifications, was employed to cut the PP sheet with the assistance of a manual press tool. Two types of PP substrates were prepared for the single lap shear test and the three-point bending test, respectively. The cut PP substrates were subsequently cleaned with ethanol to remove any surface contaminants. Finally, as shown in figure 1, target areas of 12.7 × 25.4 mm and 50.8 × 12.7 mm were marked on the PP substrates for the single lap shear test and three-point bending test, respectively.

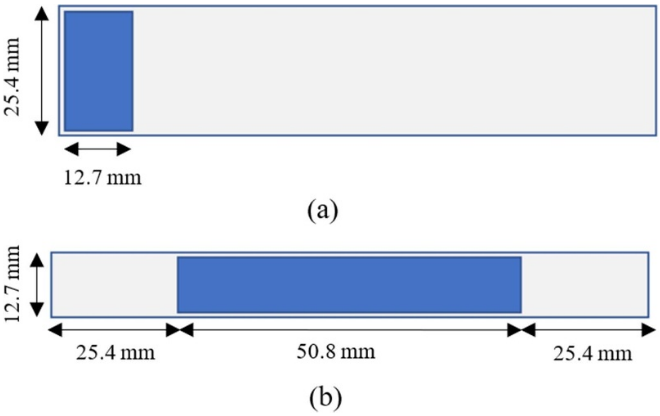

Figure 1. Top view of the target areas of PP substrates for (a) single lap shear test and (b) three-point bending test.

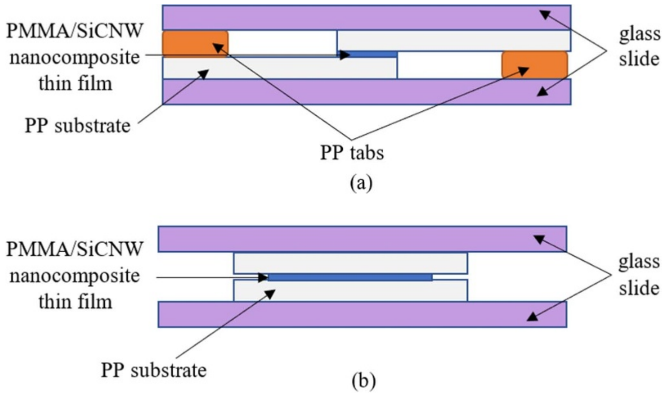

Figure 2. Schematic of the setup in microwave oven for (a) single lap shear test and (b) three-point bending test.

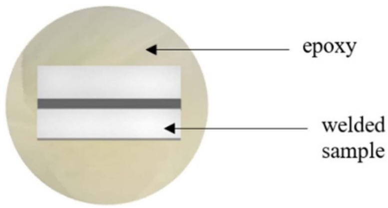

Figure 3. Sample preparation for SEM.

2.3. Preparation of PMMA SiCNW nanocomposite thin film

The PMMA/SiCNW nanocomposite thin film was fabricated using the solution casting method. To eliminate moisture content, PMMA pellets were dried in an oven at 70 °C for 24 h prior to solution casting. The dried PMMA pellets were then dissolved in acetone at a weight ratio of 1:8 and stirred for 6 h until fully dissolved. To produce nanocomposite thin films with different mass fractions of SiCNW and PMMA, varying amounts of SiCNW were added to the solution and stirred for an additional hour to ensure homogeneity. The resulting mixture was ultrasonicated for 1 h in an ultrasonic mixing bath to prevent agglomeration.

Subsequently, the ultrasonicated mixture was cast onto a Teflon plate and allowed to dry at room temperature for 24 h, forming the PMMA/SiCNW nanocomposite thin film. The fabricated nanocomposite thin films were then cut to the dimensions specified for the target areas in ASTM D3163 for the single lap shear test and ASTM D790 for the three-point bending test.

2.4. Microwave welding

In this study, a household microwave oven (Sharp R213CSR, 2.45 GHz, Sharp, Malaysia) was used to develop the welded joints. Before microwave irradiation, the cut PMMA/SiCNW nanocomposite thin film was placed on the target area of the PP substrates with the assistance of a few drops of ethanol, followed by evaporation in an oven for 10 min. The surface tension generated during the evaporation process facilitated the adhesion of the thin film to the PP substrates. An additional PP substrate was then positioned on top of the coated PP substrate, and the assembly was subjected to microwave heating. As illustrated in figure 2(a), a microwave-transparent glass slide was employed to apply pressure to the sandwiched sample, and two PP tabs were used to maintain the balance of the single lap shear test sample during the welding process. For the welded sample used in the three-point bending test, the PP tabs were removed, and the sandwiched sample, as shown in figure 2(b), was placed in the microwave oven. The microwave heating time was varied from 20 to 60 s to study the effect of heating duration, while the SiCNW loading in the nanocomposite thin film, microwave power, and clamping pressure were kept constant at 35 wt%, 800 W, and 364.93 Pa, respectively. To investigate the effect of SiCNW loading in the PMMA/SiCNW nanocomposite thin film, the mass fraction of SiCNW was varied from 35 wt% to 45 wt%, while maintaining constant microwave heating time, microwave power, and clamping pressure at 50 s, 800 W, and 364.93 Pa, respectively. After microwave heating, the sample was allowed to cool for 1 min inside the microwave oven to facilitate the solidification of the molten PP welded joint.

2.5. Characterization and testing

A scanning electron microscope (SEM, Hitachi TM3000) was used to examine the cross-section of the welded joint. Prior to examination, the welded joint was molded in a combination of epoxy resin and hardener to prevent detachment or cracking during the sectioning process. After the molded sample had hardened, it was sectioned at the center to obtain a cross-sectional sample, as shown in figure 3. The sectioned sample was then ground and polished using sandpaper of various grits to ensure a smooth and flat surface. Before SEM analysis, the sample was coated with a thin layer of platinum using a sputter coater (JFC-1600 Auto Fine Coater).

The single lap shear strength and flexural strength of the welded joints were evaluated using a universal testing machine (UTM, Instron 5569). For the single lap shear test, two PP alignment tabs, each with a thickness of 1.6 mm, were affixed to the top edge of the welded sample, as illustrated

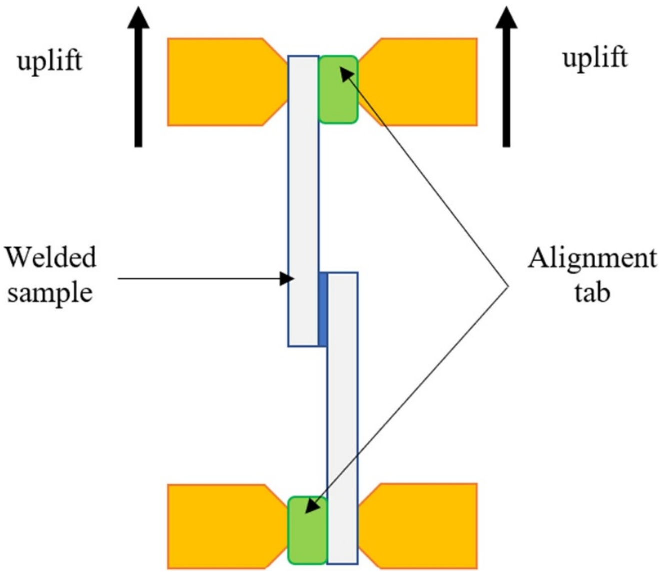

Figure 4. Setup of welded sample on UTM.

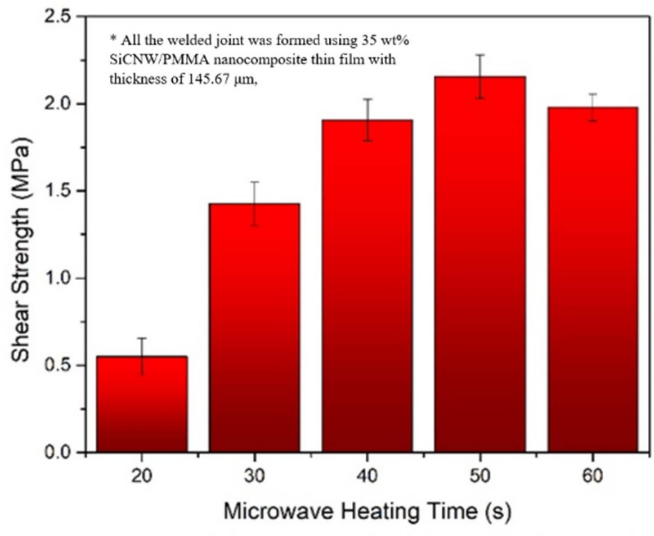

Figure 5. Comparison of shear strength of the welded joint subjected to different microwave heating time.

in figure 4, to minimize the bending moment and ensure uniform shear force distribution at the center of the welded joint. The test was conducted by pulling the welded sample apart at a crosshead speed of 1.27 mm min^{-1}, in accordance with ASTM D3163. For the three-point bending test, the support span was set at 51.2 mm, following ASTM D790, which specifies a thickness-to-support span ratio of 1:16. To determine the flexural strength and modulus of elasticity, a crosshead speed of 1.37 mm min^{-1} was applied to the welded sample until failure, as required by the ASTM standard.

3. Results and discussion

3.1. Effect of microwave heating time

Figure 5 presents the relationship between the shear strength of the welded samples and microwave heating time. In this study, the SiCNW loading in the PMMA/SiCNW nanocomposite thin film, microwave power, and clamping pressure were maintained at 35 wt%, 800 W, and 364.93 Pa, respectively. As the heating time increased from 20 to 50 s, the shear strength improved by 292.71%, reaching a maximum strength of 2.16 MPa at 50 s, as shown in figure 5. However, when the heating time was extended to 60 s, the shear strength slightly decreased to 1.98 MPa. As the microwave heating time increased from 20 to 50 s, the SiCNW were expected to absorb more energy from the microwaves and convert it into thermal energy, effectively melting the adjacent PP substrates and producing a welded joint with enhanced strength. However, prolonging the heating time to 60 s may lead to the formation of defects such as flashes and voids in the welded joint, thereby reducing its strength. Previous studies have also reported that the mechanical properties, such as the maximum load of the welded joint, increase with longer microwave heating times [21–24, 26]. For example, Xie *et al* utilized SACNT films as susceptors in microwave-assisted welding of PE substrates and found that the tensile strength of the welded samples increased from 3.78 MPa to 9.66 MPa when the heating time was extended from 30 to 75 s. They further reported that the PE matrix exhibited severe deterioration and deformation when the microwave heating time exceeded 90 s [24]. It is noteworthy that the maximum shear strength obtained using the PMMA/SiCNW nanocomposite thin-film susceptor (2.16 MPa) is higher than that of welded joints formed using a powdered SiCNW susceptor (1.86 MPa) [27]. For powdered susceptors, achieving a uniform deposition of SiCNW on the target area is challenging, leading to inconsistent amounts of susceptor. During microwave heating, the uneven distribution of susceptors results in an uneven heating rate, where regions with a higher concentration or thickness of SiCNW may experience overheating and degradation. Consequently, when tensile stress is applied, the welded joint fails at the weakest, overheated point. In contrast, when SiCNW are incorporated into a nanocomposite thin film, the uniform distribution of SiCNW and controlled film thickness are ensured. This uniformity leads to a consistent heating rate across the target area, resulting in a homogeneous welded joint without overheated spots. Therefore, when tensile stress is applied to this welded joint, the force is evenly distributed along the joint, leading to optimized strength.

Figure 6 illustrates the condition of the welded joint before and after the single lap shear test, with the red box highlighting the welded area of the sample. It is evident that the welded area was smallest when the sample was microwave-irradiated for 20 s, as shown in figure 6(a), with most of the PP substrate in contact with the PMMA/SiCNW remaining unwelded. The welded region increased significantly as the microwave heating time was extended from 20 to 60 s, achieving a fully welded joint at 50 s. However, when the sample was irradiated for 60 s, flashing of the PP substrates was observed. This behavior

Figure 6. Condition of the welded joint (a) before and (b) after subjecting to single lap shear test.

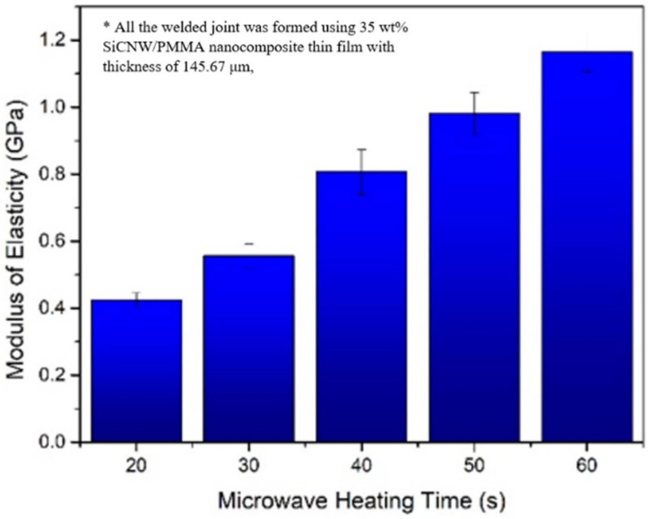

Figure 7. Modulus of elasticity of welded joint under different microwave heating time.

can be explained by the fact that when the microwave heating time reaches 50 s, the SiCNW have sufficient time to absorb the microwaves and bring the adjacent PMMA and PP matrix into a molten state, resulting in a larger welded area. However, when the microwave heating time is extended to 60 s, the heat emitted by the SiCNW may be conducted to the surface of the substrates, causing molten PP to flow out of the target area under pressure, forming a flash.

Figure 6(b) shows the condition of the welded samples after the single lap shear test. The samples welded for 20 and 30 s separated clearly upon testing, indicating adhesive failure. This type of failure can be attributed to the small and incomplete weld formed between the PP substrates, as seen in figure 6(a), which was insufficient to maintain the bond during the single lap shear test, resulting in low shear strength. For samples irradiated for 40 s and beyond, substrate failure occurred, with fractures appearing at the edge of the PP substrate adjacent to the welded joint. The welded joint became stronger than the PP substrate itself when SiCNW were integrated into the PP matrix, forming a reinforced nanocomposite layer at the joint. This explains why failure occurred in the PP substrate rather than at the welded joint. This observation aligns with findings by Sun *et al* and Wang *et al* who investigated microwave welding of thermoplastics using carbon-based materials as susceptors [21, 28]. In both studies, substrate failure was observed, and it was reported that this occurred due to the formation of a strengthened composite welded joint that was stronger than the individual thermoplastic substrates, causing failure at the edge of the substrates adjacent to the welded joint.

In microwave welding, the susceptor converts absorbed microwave energy into heat, which melts the surrounding substrates. As the SiCNW generate heat, they raise the temperature of the adjacent PMMA and PP to their melting points, forming a molten layer at the substrate interface. Under clamping pressure, the SiCNW become embedded in this molten layer, creating a reinforced nanocomposite layer at the welded joint. Thus, in this study, SiCNW served a dual function: they acted as both a susceptor and a nanofiller, enhancing the reinforcement and strength of the welded joint. Figure 7 presents the modulus of elasticity of the welded samples exposed to varying microwave heating times. The modulus increased from 0.42 GPa to 1.16 GPa as the microwave heating time was extended from 20 to 60 s. This increase is attributed to the embedding of SiCNW into the PP matrix, which strengthens the welded joint. As the microwave heating time increases, a thicker molten layer is formed, facilitating the further embedding of SiCNW and allowing them to fill a substantial depth of the PP matrix. Consequently, the modulus of elasticity of the welded joint is enhanced. A similar observation was reported by Raju *et al* who introduced SiC into epoxy resin along with nanoclay [29]. They found that the addition of high-modulus SiC inhibited the formation of microcracks, leading to improvements in Young's modulus and shear strength of the composite.

Furthermore, it is noteworthy that while the shear strength of the welded samples decreased when the microwave heating time was increased from 50 to 60 s, the modulus of elasticity of the welded samples improved. As previously mentioned, the molten PP substrate of the 60 s welded sample overflowed from the target area, causing the welded sample to become thinner. In the single lap shear test, the tensile load is applied to the overlapped area without accounting for the thickness of the welded sample [30]. Therefore, when thinning occurs, a lower tensile load is required to cause failure of the welded sample. On the other hand, the flexural modulus is inversely proportional to the thickness of the specimen. Consequently, the modulus of the 60 s welded sample increased as the thickness of the welded joint decreased due to the overflow of the PP substrate.

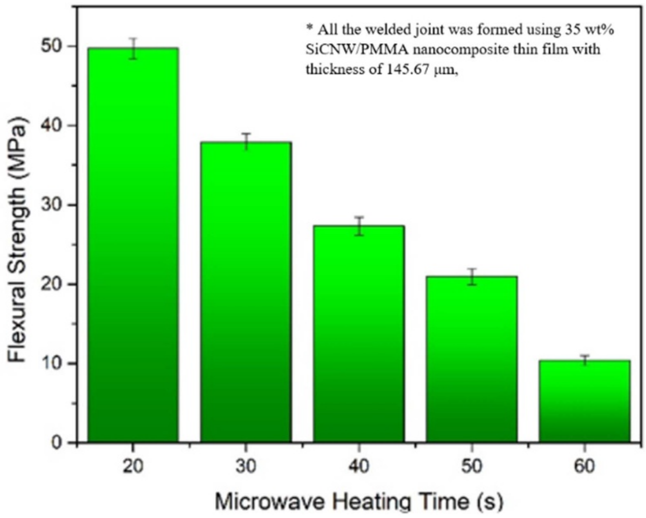

Figure 8. Flexural strength of welded joint subjected to different microwave heating time.

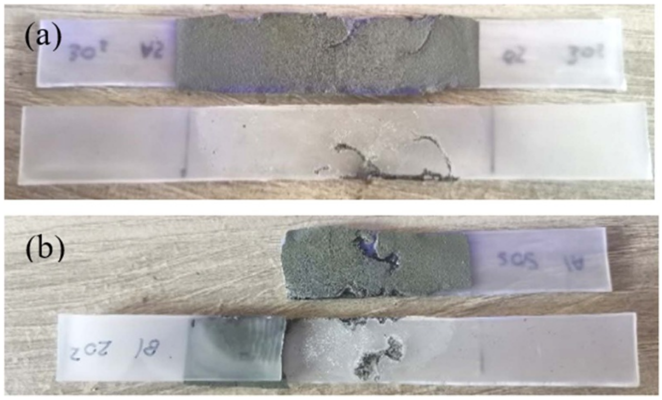

Figure 9. Photograph of (a) 30 s and (b) 50 s welded sample after three-point bending test.

Figure 8 shows the comparison of flexural strength of the welded joints under microwave heating times ranging from 20 to 60 s. The maximum flexural strength of 49.68 MPa was observed in the 20 s welded sample, and it declined steadily with increasing microwave heating time. This trend is opposite to that observed for the modulus of elasticity of the welded joints.

PP is a polymer known for its high ductility and flexibility. In the 20 s welded sample, only a small amount of SiCNW was incorporated into the PP matrix, exerting minimal restriction on the movement of the PP chains; thus, the sample maintained high flexural strength. As the microwave heating time was extended to 60 s, the thickness of the molten layer increased, allowing SiCNW to embed deeper into the PP matrix. This led to the formation of a thicker nanocomposite layer at the welded joint. When force was applied to this joint, the rigid SiCNW restricted the sliding of PP chains past each other, resulting in reduced flexural strength.

These results suggest that while the incorporation of SiCNW into the PP matrix can enhance the modulus of elasticity of the welded joint, it also reduces flexibility. A similar observation was made by Sanya *et al* in their study on the impact of SiC content in SiC/epoxy composites [31]. They found that while the flexural modulus increased with an increase in SiC content from 6 wt% to 8 wt%, the flexural strength decreased because the addition of SiC can embrittle the polymer matrix once the filler content exceeds a critical threshold.

Figure 9 presents images of the welded samples after the three-point bending test. The 20 s and 30 s welded samples display identical failure modes, where the welded samples were curved and disconnected after testing, as shown in figure 9(a). When flexural force was applied to these joints, the strength of the welded joint was insufficient to keep both PP substrates securely bonded together. This observation is consistent with the results shown in figure 6, where the welded samples detached following the single lap shear test. Figure 9(b) shows that the 50 s welded sample fractured, with one substrate separating while the other remained attached at the welded joint. The welded samples subjected to 40, 50, and 60 s of microwave heating exhibited similar failure behavior. This can be attributed to the increasing strength of the welded joint as the heating time was extended from 30 to 60 s, allowing the welded joints to maintain their integrity during the three-point bending test.

Table 1 presents the thickness of the PMMA/SiCNW nanocomposite thin film, the mean thickness of the welded joint layer, and the overall thickness of the welded samples after being subjected to microwave irradiation for 20–60 s. The cross-sectional views of the 20 s, 50 s, and 60 s welded joint layers at magnifications of 200× and 1200× are shown in figures 10(a) and (c), figures 10(d) and (f), and figures 10(g) and (i), respectively. The uniformity of the welded joint layer's thickness in the 20 s and 50 s samples, as shown in figures 10(b) and (e), was significantly improved compared to the layer formed using a powdered susceptor, as previously reported [27]. This suggests that the use of the SiCNW/PMMA nanocomposite thin film effectively serves as a susceptor, enabling the fabrication of welded joints with a homogeneous welded joint layer.

As shown in table 1, the mean thickness of the welded joint layer increases with the microwave heating time, reaching a maximum of 244.62 μm at 50 s, while the lowest mean thickness was observed in the 20 s welded joint. Additionally, figure 10(c) reveals several holes in the 20 s welded joint layer, suggesting that this short heating time was insufficient for the SiCNW to absorb an adequate amount of energy to reach the softening point of PP. Consequently, only a thin welded joint layer was formed, with visible gaps or holes between the SiCNW and the PP matrix. Moreover, as indicated in table 1, the thickness of the 20 s welded joint layer is comparable to that of the nanocomposite thin film, suggesting that this short heating duration was inadequate to liquefy the surrounding PP in contact with the PMMA/SiCNW nanocomposite thin film. The presence of holes and a thin welded joint layer is likely the primary cause of the low shear strength and modulus

Table 1. (a) Mean thickness of PMMA/SiCNW nanocomposite thin film, (b)mean thickness of welded joint layer and (c) thickness of welded sample after subjected to different heating time.

Microwave heating time (s)	(a) Mean thickness of PMMA/SiCNW nanocomposite thin film (μm)	(b) Mean thickness of welded joint layer (μm)	(c) Thickness of welded sample after microwave welding (cm)
20	145.67	146.69	3.2
30		178.11	3.2
40		214.39	3.2
50		244.62	3.2
60		152.62	3.1

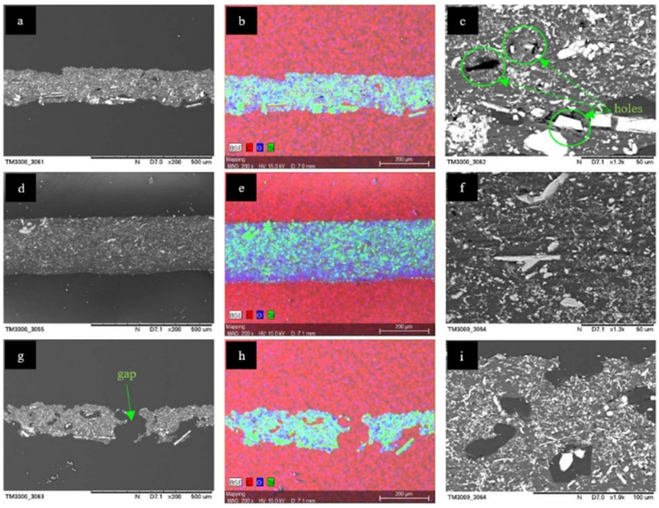

Figure 10. SEM-EDS images of welded joint layer formed under (a), (b), (c) 20 s, (d), (e), (f) 50 s and (g), (h), (i) 60 s microwave heating time at magnification 200× and 1200×.

observed in the welded joint, as discussed earlier. As the heating time was gradually increased to 50 s, the SiCNW in the PMMA/SiCNW nanocomposite thin film had more time to absorb energy, enabling the nearby PP to melt. Consequently, the molten layer thickened, and the SiCNW were uniformly and deeply embedded within the molten layer. Upon solidification, the PP matrix and SiCNW coalesced to form a welded joint that was free of any holes, as shown in figure 10(f).

Figures 10(g) and (i) show the SEM images of the 60 s welded joint at magnifications of 200× and 1200×, respectively. Table 1 provides a comparison of the thickness of the welded samples after being subjected to microwave heating times ranging from 20 to 60 s. Unlike the welded joints formed at 20–50 s, both the thickness of the welded sample and the welded joint layer were significantly reduced when a 60 s heating time was used, as shown in figure 10(g). Additionally, the thickness of welded joint layer exhibited inconsistency, with a noticeable gap where no SiCNW were present. This gap can be attributed to the excessive absorption of microwave energy by the SiCNW when the heating time was extended to 60 s, resulting in overheating and the occurrence of flashing and overflowing of PP at the welded joint, as observed in figure 6. Consequently, the welded joint layer thinned, leading to a decline in the overall strength of the welded joint.

In this study, the embedment of SiCNW into the PP substrates was verified using energy dispersive x-ray spectroscopy (EDS) elemental mapping, as shown in figures 10(b), (e) and (h). Notably, after microwave welding, the upper and lower sides of the welded samples remained unaltered, with silicon (Si) from the SiCNW and oxygen (O) from the PMMA detected only at the welded joint. This is because the microwave-transparent PP did not absorb microwave energy during irradiation; instead, the energy traveled through the PP and was absorbed by the SiCNW. Upon absorption by the SiCNW, localized heating occurred, and the heat was subsequently transferred to the adjacent PMMA matrix and PP substrate via conduction, forming a molten layer that allowed the SiCNW to embed into it under clamping pressure. Due to the low thermal conductivity of PP, it acted as a cooling reservoir, minimizing heat transfer to the surface of the PP substrates. After cooling and solidification, a sandwiched structure consisting of PP/SiCNW-reinforced PP/PP was formed at the welded joint. A similar observation was reported by Wang *et al* who investigated the welding of multi-walled CNTs (MWCNTs) to poly(ethylene terephthalate) (PET) [28]. Their results demonstrated that MWCNTs were completely intercalated into the PET matrix after short-term microwave heating (e.g. 1 s), while the top side of the PET substrates remained intact and free of MWCNTs. They attributed this finding to the significant difference in thermal conductivity between MWCNTs and PET, which resulted in low final temperatures at the PET surface. This thermal resistance was considered advantageous in microwave welding, as it prevents damage to the PET from rapid heating.

3.2. *Effect of filler loading of SiCNW in PMMA/SiCNW nanocomposite thin film*

The filler loading of SiCNW significantly influences the dielectric properties and microwave-absorbing capability of the PMMA/SiCNW nanocomposite thin film. As the weight percentage of SiCNW in the nanocomposite thin film increases, it is expected that both the dielectric properties and microwave absorption capacity will also increase, due to the greater availability of SiCNW to absorb microwave energy. Consequently, this leads to more heat being generated and, in

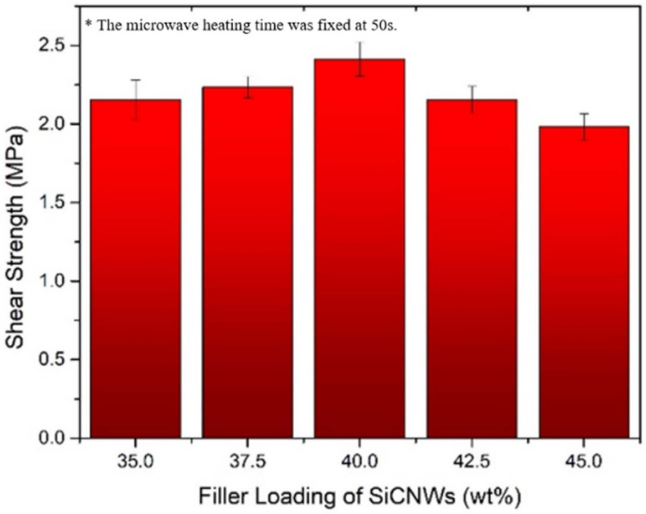

Figure 11. Shear strength of microwave welded joint as a function of filler loading of SiCNW in PMMA/SiCNW nanocomposite thin film.

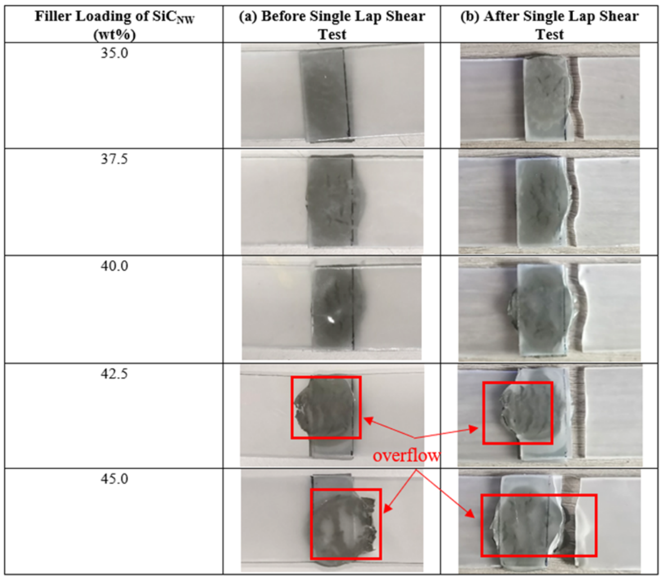

Figure 12. Condition of welded joint (a) before and (b) after subjected to single lap shear test.

turn, a higher heating rate for the PMMA/SiCNW nanocomposite thin film. For example, Pal *et al* investigated the dielectric properties of SiC-reinforced epoxy composites and found that the real part of permittivity, the imaginary part of permittivity, and the dielectric loss tangent all increased as the SiC loading increased from 10 wt% to 30 wt% [32]. Based on these findings, this study also examined the effect of varying the filler loading of SiCNW in the PMMA/SiCNW nanocomposite thin film, ranging from 35 wt% to 45 wt%, while maintaining constant microwave heating time (50 s), microwave power (800 W), and clamping pressure (364.93 Pa).

Figure 11 shows the shear strength of welded joints formed using PMMA/SiCNW nanocomposite thin films with varying SiCNW filler loadings as susceptors. The shear strength of the welded joint formed with a 35 wt% PMMA/SiCNW nanocomposite thin film was recorded at 2.16 MPa, and it increased by approximately 11.57% to 2.41 MPa when a 40 wt% filler loading was used. As mentioned earlier, the filler loading of SiCNW significantly affects the heating rate of the nanocomposite thin film. When a nanocomposite thin film with a higher SiCNW loading is subjected to microwave irradiation, a more rapid heating rate is obtained. Consequently, a molten layer of increasing thickness forms at the joining interface, with more SiCNW embedded within the molten layer. Upon cooling, this results in a thicker nanocomposite welded joint, which leads to optimized joint strength. This finding is consistent with the results reported by Staicovici *et al* who demonstrated that the joint strength of high-density PE increased as the amount of polyaniline (PANI) susceptor was increased [25]. They further asserted that the enhanced strength of the welded joint was due to the increased thickness of the molten layer created by the PANI susceptor.

The maximum shear strength obtained in this study (2.41 MPa) is noteworthy, as it exceeds the maximum shear stress achieved by Sun *et al* (2.09 MPa) in their investigation of welding PP substrates using nano-graphite as a susceptor [21]. This difference may be attributed to the use of different susceptors, which can result in varying heating rates. This hypothesis is supported by research conducted by Patel *et al* who studied the microwave heating capabilities of various microwave susceptors [13]. They found that SiC has a higher microwave heating rate than graphite and pulverized carbon, which they attributed to the strong dipole interactions of SiC in an oscillating electric field, leading to a high dielectric loss factor. Additionally, the structural differences between nano-graphite, which is particulate, and SiCNW, which are whisker-like, can influence their effective surface areas and reinforcement mechanisms. This observation is consistent with a study by Denver *et al* who compared the mechanical properties of polydimethylsiloxane (PDMS) composites filled with nickel nanoparticles and nanowires [33]. They reported that the mechanical properties of PDMS composites filled with nickel nanowires were 50% higher than those filled with nickel nanoparticles due to the greater effective surface area of the nanowires, which resulted in stronger interfacial interactions between the polymer and the filler. Given these considerations, SiCNW may have a higher microwave absorption and heating rate, as well as a more effective surface area compared to nano-graphite, which could explain the higher joint strength observed in this study. However, the shear strength of the welded joint decreased from 2.41 MPa to 1.98 MPa when the SiCNW filler loading in the nanocomposite thin film was further increased from 40 wt% to 45 wt%. This reduction is likely due to overheating at the welded joint caused by the high heating rate, leading to defects and deformation in the welded sample.

Figure 12 depicted the photograph of welded sample formed utilizing PMMA/SiCNW nanocomposite thin film with varying filler loading of SiCNW as susceptors before and after single lap shear test was conducted. When these welded samples were underwent single lap shear test, substrates failure was observed, with the fracture occurring at the PP substrate contiguous with the welded joint. This is since the heat dissipated by SiCNW is able to entirely melt the PMMA and the PP matrix at the tarobtained area and create a thick molten layer. Following that, the SiCNW were incorporated into the created PMMA-PP molten layer and formed a nanocomposite welded joint that exhibits superior strength in comparison to the plain PP substrates. When shear stress is exerted to the welded sample, the stress is concentrated at the border of nanocomposite welded joint and the PP substrates and hence, the sample break at the edge of the welded joint Wang *et al* made a similar observation when they subjected welded polycarbonate (PC)/MWCNTs/PC to peeling test [28]. They claimed that this type of substrate failure denoted that the bonding between the PC substrates is stronger than the PC substrate itself. However, flashing and overflowing was observed for both 42.5 wt% and 45 wt% welded sample. When excessive loading of SiCNW is used, the heating rate is tough to be too high and the heat is transferred to the outer surface of PP substrates. Under clamping pressure, the molten PP was pushed to flow out from the tarobtain area and thus, cautilizing the thickness reduction in the welded sample. This flashing of PP is believed to be the reason for lowered shear strength in 42.5 wt% and 45 wt% welded sample.

Figures 13(a) and (b) illustrate the modulus of elasticity and flexural strength of the welded joint as a function of the filler loading of SiCNW in the PMMA/SiCNW nanocomposite thin film, respectively. An increase of 62.24% in the elastic modulus was observed when the filler loading of SiCNW was raised from 35 wt% to 45 wt%. While the incorporation of rigid SiCNW into the PP matrix improved the shear strength and modulus of elasticity of the welded joint, it is important to note that this enhancement came at the cost of flexibility. The highest flexural strength, 20.94 MPa, was achieved with the 35 wt% welded sample. Beyond this point, the flexural strength decreased steadily, reaching the lowest value of 10.47 MPa for the 45 wt% welded sample.

SiCNW are well-known ceramic materials with exceptional characteristics, including high strength and a high elastic modulus, when used as nanofillers in the formation of nanocomposites [34]. As previously mentioned, the welded joint was strengthened after the SiCNW were embedded into the PP-PMMA molten layer. Similarly, when rigid SiCNW are positioned between the PP-PMMA chains, the polymer chains cannot glide freely under applied force, thereby constraining the mobility of both PP and PMMA chains. Consequently, as the filler loading of SiCNW in the PMMA/SiCNW nanocomposite thin film increases, the modulus of the welded joint increases while the flexural strength decreases.

This finding is consistent with the results reported by Rana *et al* who studied the impact of aluminum (Al) and silicon carbide (SiC) on the mechanical properties of epoxy hybrid composites [35]. Their results demonstrated a similar trend in Young's modulus and flexural strength as a function of SiC weight percentage. They observed that the Young's modulus of the SiC-Al/epoxy composite increased, while the flexural strength decreased when the SiC loading was increased from 5 wt% to 25 wt%. They attributed this trend to the incorporation of high-stiffness SiC into the soft epoxy matrix, where the mobility of the polymer chains was restricted by the SiC, necessitating a higher force to bring the sample to failure.

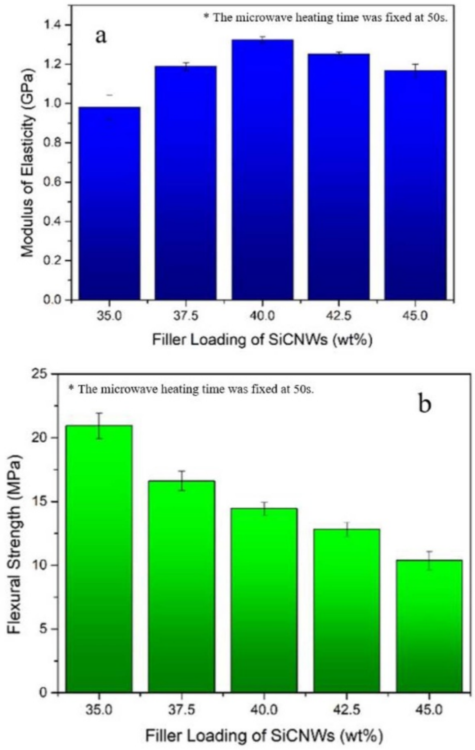

Figure 13. (a) Modulus of elasticity and (b) flexural strength of welded joint against filler loading of SiCNW.

Furthermore, it is noteworthy that the trend in the modulus of elasticity of the welded joint is opposite to that of the shear strength as the loading of SiCNW increases from 40 wt% to 45 wt%. While the shear strength shows a decreasing trend, the modulus of elasticity increases. This behavior can be attributed to the overflow and thinning of the PP substrates at the welded joint, as illustrated in figure 12. In the single lap shear test, the strength is directly proportional to the applied force, with thickness not being considered. As the PP welded joint becomes thinner, a smaller force is sufficient to cause failure, leading to a decrease in shear strength due to the overflow of molten PP. Conversely, the modulus of elasticity is inversely proportional to the thickness of the welded joint. Therefore, as thinning occurs at the welded joint, the modulus of elasticity increases.

Figure 14 shows a photograph of the 40 wt% welded sample after the three-point bending test. All welded samples with SiCNW loadings ranging from 35 wt% to 45 wt% fractured completely at the welded joint, as illustrated in figure 14 (with the 40 wt% sample as an example). The deep embedment of SiCNW into the PP matrix enhances the overall toughness

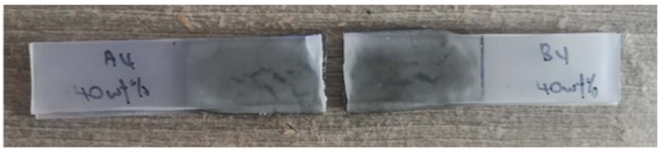

Figure 14. Photograph of 40 wt% welded sample after being subjected to three-point bending test.

Table 2. Mean thickness of PMMA/SiCNW nanocomposite thin film, (b) mean thickness of welded joint layer and (c) thickness of welded sample formed with different loading of SiCNW.

Loading of SiCNW (wt%)	(a) Mean thickness of PMMA/SiCNW nanocomposite thin film (μm)	(b) Mean thickness of welded joint layer (μm)	(c) Thickness of welded sample after microwave welding (cm)
35.0	145.67	246.66	3.2
37.5	172.63	273.82	3.2
40.0	187.41	302.24	3.2
42.5	193.20	309.74	3.1
45.0	200.01	341.15	3.0

of the welded joint; however, it simultaneously reduces its flexibility and ductility. Consequently, the welded samples exhibit behavior characteristic of brittle materials, fracturing completely at the center of the welded joint. This observation aligns with the results obtained in the three-point bending test, as presented in figure 13.

Table 2(a)–(c) present the mean thickness of the PMMA/SiCNW nanocomposite thin film, the mean thickness of the welded joint layer, and the thickness of the welded samples formed using PMMA/SiCNW nanocomposite thin films with filler loadings ranging from 35 wt% to 45 wt%, respectively. As expected, the mean thickness of the PMMA/SiCNW nanocomposite thin film increases with higher SiCNW loading. Similarly, the mean thickness of the welded joint layer also increases with greater filler loading. The 35 wt% welded joint exhibited the minimum thickness of 246.66 μm, while the 45 wt% welded joint achieved the maximum thickness of 341.15 μm. SEM images of the 35 wt% and 40 wt% welded joints at magnifications of 200× and 1200× are shown in figures 15(a) and (c) and figures 15(d) and (f), respectively. When a PMMA/SiCNW nanocomposite thin film with a lower filler loading was used, fewer SiCNW were available to interact with the microwave, resulting in less heat being generated to melt the surrounding PP matrix. Consequently, a welded joint layer with reduced thickness was formed. In addition, the thickness of the welded joint layer was found to be non-uniform when a PMMA/SiCNW nanocomposite thin film with a lower filler loading (e.g. 35 wt%, as shown in figure 15(b)) was used. Conversely, with a higher filler loading (e.g. 40 wt%), a thicker molten layer was produced, with the SiCNW uniformly embedded within it. This resulted in a nanocomposite welded joint layer that was both more uniform and thicker, as illustrated in figure 15(e). The incorporation of SiCNW in the welded joint layer was further confirmed by EDS elemental mapping, as shown in figures 15(b), (d) and (e). Additionally, a homogeneous dispersion was observed in both welded joint layers, although

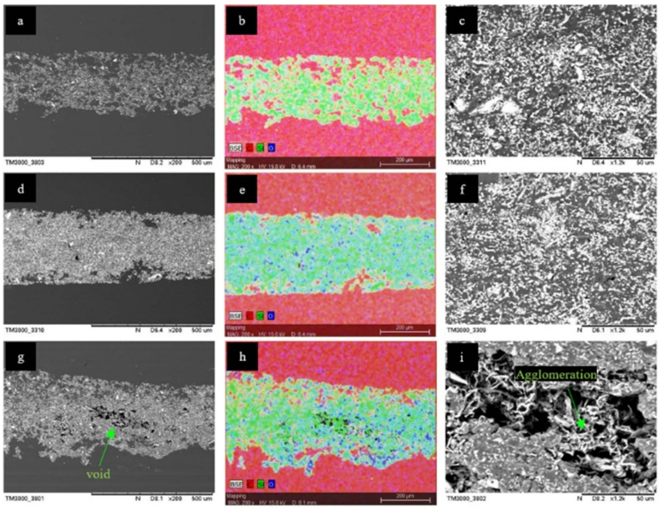

Figure 15. SEM-EDS image of welded joint layer formed with (a), (b), (c) 35 wt%, (d), (e), (f) 40 wt% and (g), (h), (i) 45 wt% loading of SiCNW at magnification 200× and 1200×.

the distribution of SiCNW was denser in the 40 wt% welded joint, as evident in figures 15(c) and (f). This denser nanocomposite structure is believed to contribute to the enhanced shear strength and modulus of the welded joints formed with increasing filler loadings from 35 wt% to 40 wt%. These findings align with those reported by Xie *et al* who studied the welding of PE using SACNT films with microwave radiation [24]. They also observed that no other parts of the PE substrate's structure were affected by microwave heating, which occurred only at the interface in contact with the SACNTs. The incorporation of SACNTs into the PE substrates strengthened the welded joint, resulting in optimized tensile strength at the welded interface.

Figures 15(g) and (i) show the SEM images of the 45 wt% welded joint at magnifications of 200× and 1200×, respectively, while figure 15(h) presents the EDS elemental mapping of the sample. It is noteworthy that the mean thickness of the PMMA/SiCNW nanocomposite thin film and the welded joint layer display an opposite trend compared to the overall thickness of the welded sample after microwave welding when the SiCNW filler loading in the PMMA/SiCNW nanocomposite thin film exceeds 40 wt%. Although the mean thickness of the welded joint layer increases, voids and agglomerates are observed within the joint layer, as shown in figures 15(g) and (i). Due to their high surface energy, SiCNW tend to agglomerate to minimize this energy. However, such agglomerates do not provide benefits in microwave welding. Excessive SiCNW content can result in an uneven heating rate and void formation in the nanocomposite, as they are unable to be uniformly embedded within the molten layer during the welding process. This, in turn, results in a non-uniform thickness of the welded joint layer. These voids subsequently act as stress concentrators when tensile force is applied, leading to a reduction in shear strength. Nevertheless, the presence of agglomerates does not diminish the modulus of elasticity or the flexural strength of the welded joint. This may be because the high SiCNW content generates a high heating rate, causing a significant amount of molten SiCNW/PP to spill out from the target area. Consequently, the thickness of the welded sample decreases, optimizing the modulus of the welded joint, while the flexural strength deteriorates, as discussed earlier.

3.3. Formation mechanism of SiCNW/PP nanocomposite welded joint

Microwaves are a form of electromagnetic radiation consisting of alternating and perpendicular electric and magnetic fields. Since SiCNW are dielectric and dipolar materials without magnetic properties, they interact solely with the electric field component of the microwave, and magnetic loss does not affect their absorption performance [36]. For dielectric materials to function as microwave susceptors, it is essential to evaluate their complex relative permittivity and loss tangent factor to determine their microwave absorption performance. According to Al-Mattarneh, the microwave absorption performance of a material is related to its complex relative permittivity, ε_r which can be determined using equation (1) [37]. In addition, the loss tangent factor is a crucial component for a microwave susceptor. The loss tangent factor, $\tan\delta$, as defined in equation (2), represents the effectiveness with which a material converts microwave energy into thermal energy [38]. As noted by Wu and Benatar, the heating rate of the susceptor is directly proportional to the loss tangent factor [39],

$$\varepsilon_r = \varepsilon_r{}' - j\varepsilon_r{}'' \quad (1)$$

$$\tan\delta = \varepsilon_r{}''/\varepsilon_r{}'. \quad (2)$$

In this context, $\varepsilon_r{}'$ denotes the material's ability to store electric energy, while $\varepsilon_r{}''$ represents the material's ability to lose electric energy, and j is defined as $j^2 = -1$. As mentioned earlier, SiCNW are dielectric materials that interact only with the electric component of microwaves. To function as an ideal susceptor, SiCNW must exhibit high values for both the dielectric constant and the loss tangent factor, ensuring exceptional microwave absorption performance. Previous studies have reported that SiC nanomaterials possess a high dielectric constant, a significant tangent loss factor, and strong microwave-absorbing abilities, making SiCNW effective susceptors [36, 40, 41]. Being a dipolar material, SiCNW are rich in dipoles within their molecular structure. When SiCNW are not exposed to an electric field, their dipoles are randomly oriented, resulting in no net dipole moment, as the vector sum of the dipoles is zero. Under these conditions, no energy is lost, and the SiCNW do not heat up. However, when an external electric field is applied across SiCNW, a dipole moment is created. As microwaves contain both alternating electric and magnetic fields, the dipoles within the SiCNW absorb energy from the electric field, causing them to align and rotate in the direction of the field. Since the electric field alternates, the dipoles continually rotate back and forth, a phenomenon known as dipolar polarization. Various forces, including inertial, elastic, and frictional forces, hinder this realignment process, leading to energy loss in the form of heat, which is subsequently dissipated into the environment. Thus, dipolar polarization and the associated energy loss are the primary heating mechanisms in SiCNW.

Since the thermoplastic substrate PP used in this work is microwave transparent, SiCNW were selected as the susceptor to absorb microwave energy and melt the joining interface of the PP substrates. In this study, SiCNW were first embedded into a PMMA matrix to form a PMMA/SiCNW nanocomposite thin film, which was then used as the susceptor. PMMA is a polar thermoplastic material with dielectric properties. According to the findings reported by Lu *et al* PMMA has a dielectric constant of approximately 4, which is higher than that of non-polar polymers like PP [42]. This property allows PMMA to effectively absorb microwaves, facilitating the microwave welding process. Furthermore, PMMA also serves as a host to hold the SiCNW in place during the fabrication of the nanocomposite thin film. Fabricating the susceptor in a thin film form ensures a uniform heating rate during microwave irradiation and ease of handling. The formation mechanism of the SiCNW/PP nanocomposite at the PP interface via microwave welding is schematically illustrated in figure 16. Prior to use as a susceptor, SiCNW were compounded with PMMA to create a nanocomposite thin film. This PMMA/SiCNW film was then clamped at the target area of the PP substrates, and the entire specimen was exposed to microwave radiation. To prevent damage to the substrate surface or the microwave oven, a microwave-transparent glass block was employed to provide pressure and maintain close contact at the target area. Due to the large penetration depth of microwave-transparent materials, the incident microwaves passed through the glass block and PP substrate without interacting with them, directly reaching the PMMA/SiCNW nanocomposite thin film. The dipoles within the SiCNW absorbed the microwave energy, causing them to realign according to the alternating electric field, which resulted in heat dissipation.

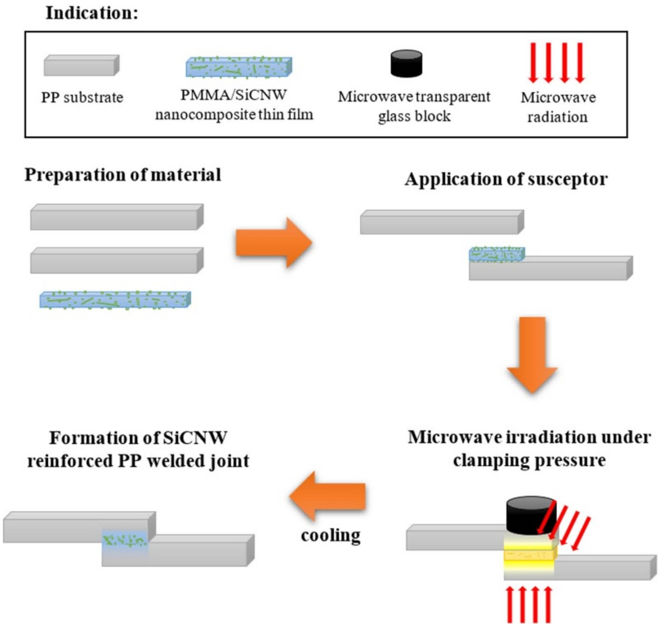

Figure 16. Schematic representation of microwave welding of PP substrates utilizing PMMA/SiCNW nanocomposite thin film as susceptor.

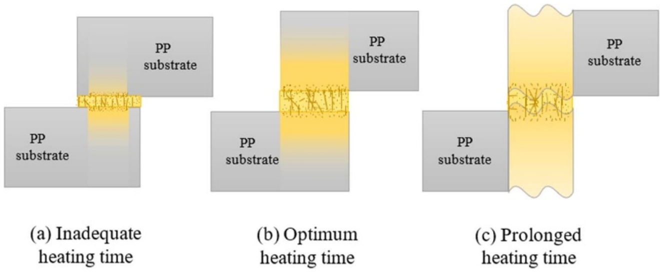

Figure 17. Condition of the welded joint subjected to (a) inadequate, (b) optimal and (c) prolonged microwave heating time.

This heat was then transferred by conduction, first to the PMMA matrix and subsequently to the surrounding PP substrates, thereby melting the PMMA/SiCNW nanocomposite thin film at the PP interface. Simultaneously, the clamping pressure drove the SiCNW into the molten PP, facilitating polymer chain entanglement across the interface. The heating rate at the PP substrates was substantially slower than at the SiCNW susceptor due to the poor thermal conductivity of PP. This slower heating rate is advantageous, as it prevents damage or degradation to the upper surface of the PP substrates. After microwave irradiation, the welded joint was allowed to cool, enabling the molten PP to resolidify and form a SiCNW/PP nanocomposite welded joint. In summary, SiCNW served dual roles in this study: as a microwave susceptor to absorb microwave energy and as a nanofiller to reinforce the welded joint.

As mentioned earlier, microwave heating time has a significant influence on the mechanical properties and cross-sectional microstructure of the microwave-welded joint. In essence, the microwave heating time determines the amount of microwave energy emitted from the magnetron. The longer the heating time, the longer the magnetron operates, and the more microwave energy is transmitted. Consequently, SiCNW can absorb more microwave energy, resulting in greater heat generation and melting of the surrounding PP substrates. Figure 17 illustrates three possible scenarios for the welded joint when microwave heating is applied for insufficient, optimal, and extended durations. In the first scenario, depicted in figure 17(a), the heating time is too short, and the SiCNW do not absorb sufficient energy. As a result, only a shallow depth of the PP substrates experiences a temperature rise. Due to the inadequate heat generated by the SiCNW, the periphery of the target area remains unheated. Additionally, the limited depth of the heated region prevents the SiCNW from fully embedding into the molten PP matrix, with most SiCNW remaining at the interface. This results in a weak welded joint. Under optimal microwave heating time, more energy is absorbed by the SiCNW, and the heat emitted is sufficient to completely melt the entire target area. As illustrated in figure 17(b), the heat is conducted to a greater depth within the PP substrates, leading to the formation of a thicker molten layer. This thicker molten layer allows the SiCNW to be fully embedded, facilitating the formation of a robust nanocomposite welded joint upon cooling. Consequently, the mechanical properties of the welded joint are optimized. However, when microwave heating is prolonged, distortion of the PP substrate may occur, as shown in figure 17(c). Excessive microwave irradiation causes an excessive amount of heat to be generated, resulting in a temperature rise throughout the entire depth of the PP substrates. Under clamping pressure, the surface of the substrates may flow out of their original positions, causing distortion in the welded joint. This distortion can reduce the thickness of the welded joint, subsequently diminishing the strength of the welded sample.

In addition to microwave heating time, the amount of SiCNW can also influence the heating rate of the susceptor, which may ultimately affect the properties of the welded joint. It has been observed that the thickness of the PMMA/SiCNW nanocomposite thin film increases with a higher mass fraction of SiCNW in the PMMA matrix. For a fixed amount of PMMA, the thickness of the thin film is directly affected by the amount of SiCNW; a greater quantity of SiCNW results in a thicker nanocomposite thin film. Consequently, the mechanical properties of the welded joint are also impacted by the thickness of the PMMA/SiCNW nanocomposite thin film. Figure 18 presents a schematic diagram of the welded joint formed with insufficient, optimal, and excessive amounts of SiCNW as susceptors. In figure 18(a), when the amount of SiCNW is insufficient, only a thin molten layer is created. This occurs because, with a low mass fraction of SiCNW in the PMMA/SiCNW nanocomposite thin film, the film is predominantly composed of the microwave-transparent PMMA matrix, with a limited amount of SiCNW. As a result, fewer SiCNW act as susceptors to absorb microwave energy and dissipate heat, leading to a slower heating rate and melting only a shallow depth of the PP substrate. Consequently, a

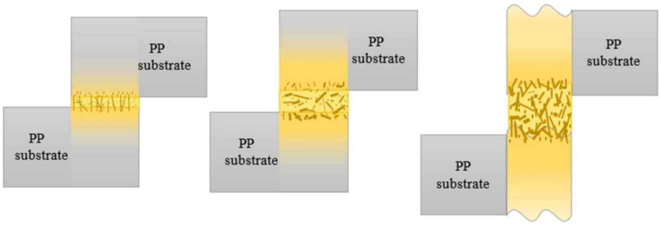

Figure 18. Condition of welded joint formed utilizing (a) insufficient, (b) optimal and (c) excessive amount of SiCNW.

welded joint with low strength is developed. In cases where the amount of SiCNW is extremely low, the interface of the PP substrates may not be heated adequately, and a welded joint cannot be formed due to insufficient heat dissipation by the SiCNW. In contrast, figure 18(b) shows a scenario where heat is conducted to a greater depth within the PP substrates. As the mass fraction of SiCNW in the nanocomposite thin film increases, more SiCNW are available to serve as susceptors, effectively melting the PMMA matrix and PP, resulting in a thicker molten layer. More SiCNW are embedded into this molten layer, leading to a thicker and stronger SiCNW-reinforced PP nanocomposite welded joint. Figure 18(c) illustrates the potential outcome when an excessive amount of SiCNW is used in the PMMA/SiCNW nanocomposite thin film as a susceptor. During the fabrication of the nanocomposite thin film, agglomeration and aggregation may occur if the mass fraction of SiCNW is too high, resulting in an uneven distribution of SiCNW within the thin film and inconsistent heating rates across the PP substrates. Furthermore, an excess of SiCNW may cause overheating of the PP substrate, as the heat dissipated from the SiCNW becomes excessive and is transferred to both the upper and lower surfaces of the PP substrates. This can lead to deterioration of the PP substrates, such as the formation of flashes and voids under clamping pressure, ultimately resulting in a welded joint with reduced strength.

4. Conclusion

This study demonstrates the effectiveness of using PMMA/SiCNW nanocomposite thin films as susceptors in the microwave welding of PP substrates, leveraging their superior dielectric properties and ability to provide homogeneous heating. The SiCNW within the nanocomposite absorb microwave energy, generate heat through dipolar polarization, and release this heat to melt the adjacent PP matrix. Additionally, the SiCNW serve as nanofillers, integrating into the PP-PMMA molten layer to form a robust nanocomposite welded joint upon cooling and solidification. The results reveal that the cross-sectional microstructure and mechanical properties of the welded joint are significantly influenced by both the microwave heating time and the filler loading of SiCNW in the nanocomposite thin film. An optimal microwave heating time led to notable improvements in the joint's mechanical properties, with shear strength increasing from 0.55 MPa to 2.16 MPa and the elastic modulus from 0.42 GPa to 0.98 GPa when heating time was extended from 20 to 50 s. However, extending the heating time beyond 50 s resulted in deformation and a decline in mechanical performance. Similarly, the SiCNW filler loading in the nanocomposite thin film had a pronounced impact on joint strength. The shear strength improved from 2.16 MPa to 2.41 MPa as the loading increased from 35 wt% to 40 wt%, but decreased with further loading beyond 40 wt% due to agglomeration and thinning of the welded sample. While increasing the content of high-rigidity SiCNW enhanced the modulus of the welded joint, it also led to embrittlement and reduced flexibility. These findings suggest that an optimized welded joint can be achieved through carefully controlled microwave heating time and SiCNW loading, enabling efficient short-term microwave irradiation. This study presents a promising, safe, and time-efficient approach to material joining using microwave heating, with potential applications in various fields requiring advanced welding techniques.

Data availability statement

The data cannot be made publicly available upon publication because they contain commercially sensitive information. The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Author contributions

Phey Yee Foong—Writing—Original Draft, Methodology; Chun Hong Voon—Conceptualization, Writing—Review & Editing, Supervision; Bee Ying Lim—Data Curation; Pei Leng Teh—Supervision; Cheow Keat Yeoh—Formal Analysis; Mohd Afendi Bin Rojan—Supervisor; Nor Azizah Parmin—Data Curation; Subash C. B. Gopinath—Visualization; Foo Wah Low—Investigation; Muhammad Kashif—Investigation; Nor Azura Abdul Rahim—Validation; Sung Ting Sam—Validation; Veeradasan Perumal—Validation.

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