

Effect of Microwave Power and Clamping Pressure on the Microwave Welding of Polypropylene Using Silicon Carbide Nanowhiskers as Microwave Susceptor

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Abstract Due to their excellent dielectric properties and the rapid response to microwave irradiation, silicon carbide nanowhiskers (SiCNWs) were employed as microwave susceptor in this study to absorb microwave and locally melt the surrounding polypropylene (PP) substrates for the joining of PP substrates. Complete welded joint is formed after the melted PP was cooled and resolidified. Other than microwave susceptor, SiCNWs also acted as the nanofillers in strengthening the welded joint through the formation of SiCNWs reinforced PP nanocomposite at the interface of PP substrates. Besides, the effect of microwave power on the microwave welding of PP substrates using SiCNWs as susceptor was studied and reported. It was found that the tensile strength and modulus of elasticity of the welded joint improved as microwave power increased. However, it deteriorates the flexibility of the welded joint as high stiffness SiCNWs were incorporated deeper into the PP matrix which restricted the PP chain mobility. Aside from microwave power, clamping pressure is also critical in determining the mechanical properties of a welded joint. When compared to unclamped welded joint, the tensile strength, modulus of elasticity and flexibility of welded joint subjected to clamping pressure improved drastically. Moreover, the tensile strength of welded joint increased when the clamping pressure was increased from P1 to P3, but decreased when the clamping pressure was further increased to P4 due to the occurrence of flashing at welded joint. The formation mechanism of SiCNWs reinforced PP welded joint was also proposed in this study. Compared to conventional welding, this welding process is easy, straightforward and is able to produce welded joint with outstanding mechanical properties *via* precise controlling of the processing parameters. Thus, microwave welding is thought to offer an option for the joining of thermoplastics and other applications.

Keywords Microwave welding; Silicon carbide; Nanowhiskers; Joining; Susceptor

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INTRODUCTION

Microwave is an electromagnetic radiation with frequency ranging from 300 MHz to 300 GHz. Microwave heating, in general, is a process in which a material couples with microwaves, absorbs and transforms the microwave energy into heat. Microwave heating offers benefits such as rapid heating rates, low processing temperature, short processing time and low energy consumption.^[1–3] Microwave heating is well-developed and is seen widely commercialised in various

applications. However, microwave welding is rarely reported because it is a relatively new technique among the welding methods. Microwave welding is a type of electromagnetic welding that works with microwave heating. Microwave welding not only makes use of the advantages of microwave heating, it also provides benefits such as its ability to be applied to components of any complicated form or dimension, simplicity of disassembly and controllable heating rate.^[4–6] As a result, several efforts of studying and improving microwave welding have been attempted.

Nonetheless, most of the reported studies focused on the microwave welding of metallic materials with only limited studies reporting on the microwave welding of thermoplastics. The reason for this is because most of the thermo-

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plastics are microwave transparent materials with linear hydrocarbon chains without polar groups or free electrons within their molecules. For this reason, microwave susceptor is required at the thermoplastic interface for the microwave welding of thermoplastics. Microwave susceptor is a class of highly lossy materials which have excellent microwave absorbing ability and capable of efficiently converting it into heat energy even at ambient temperature.^[7] Previous studies showed that conductive carbon materials such as carbon nanotubes (CNTs) and graphite can be used as susceptor for microwave welding due to the presence of delocalized sp^2 π electrons.^[8–11] For example, microwave welding of 3D printed polylactic acid (PLA) by using CNTs coating was reported by Sweeney *et al.* They observed that after 60 s of microwave irradiation, the fracture strength of the welded joint improved by 275% compared to baseline 3D printed PLA coupons.^[12] Besides, Sun *et al.* demonstrated the microwave welding of polypropylene (PP) using graphite as the susceptor.^[8] High bonding strength of welded joint was observed and they claimed that this high bonding strength of PP welded joint was attributed to the formation of PP/graphite composite at the interface. According to these studies, microwave welded joint formed using carbon materials as susceptor can exhibit superior mechanical properties and it is a rapid process in which welded joint can be formed in less than a minute. Yet, carbon materials are known to be hazardous to human health because they suppress human immune system and cause lungs inflammation.^[13]

Other than carbon materials, intrinsically conducting polymer such as polyaniline (PANI) and polypyrrole (PPy) were also studied and reported for the use as susceptor for microwave welding of thermoplastics.^[14,15] Wu and Benatar, for example, developed a microwave joining method using high density polyethylene (HDPE) as thermoplastic material and PANI as susceptor *via* butt joint design. They reported that the bonding strength is greatly influenced by the thickness of molten layer and heating rate. Furthermore, given the proper conditions, the bonding strength of the welded joint can achieve the strength of bulk HDPE.^[15] However, additional steps were required before intrinsically conductive polymer can be used as microwave susceptor because intrinsically conductive polymer must be doped with additional acidic dopant to introduce free electrons into their molecular structure. After the introduction of free electrons, their electrical conductivity and microwave absorption capability are greatly enhanced, hence, making them a viable option for microwave susceptor.

Among many types of microwave susceptors, silicon carbide (SiC) has received considerable attention, and it has been described as one of the most promising microwave susceptors. Basically, SiC is a kind of dielectric and polar material with high loss factor, which makes it a potential microwave susceptor.^[16–18] An ideal microwave susceptor should not only possess impressive microwave susceptibility, but also requires some other properties such as lightweight, good mechanical properties and environmentally stable. Silicon carbide nanomaterials (SiCNMs) are inorganic ceramic nanomaterials composed of covalently bonded carbon and silicon atoms, thus making them lightweight with notable mechanical properties, high chemical inertness and thermal stability,

and hence, they are ideal microwave susceptors.^[19,20] Besides, previous studies also show that the microwave absorption performance of SiCNMs was significantly enhanced compared to the micro-sized SiC due to their high specific surface area and interface polarisation.^[21,22] Therefore in this study, silicon carbide nanowhiskers (SiCNWs) was employed as a microwave susceptor for microwave welding of thermoplastic.

Previous studies showed that the microwave heating rate has a substantial effect on mechanical properties such as weld strength of the welded joint and the thickness of the molten layer.^[6,23] Heating rate not only can be controlled by the amount of susceptor, it can also be controlled by microwave power level as reported by Suriapparao *et al.* in which a higher power level resulted in a higher heating rate.^[24] Additionally, clamping pressure is crucial in microwave welding because pressure is necessary to promote the occurrence of chain entanglement across the interface between the molten thermoplastic. Up to present, no study on the effect of microwave power and clamping pressure on the mechanical properties and cross-sectional microstructure of microwave welded joint using silicon carbide nanowhiskers (SiCNWs) as susceptor was reported. Therefore, the effect of microwave power level and clamping pressure on the mechanical properties and microstructure of cross-section was studied and reported in this study. We also proposed the formation mechanism of SiCNWs reinforced PP welded joint in this study.

EXPERIMENTAL

Materials

SiCNWs was purchased from Nanostructured & Amorphous Material Inc., USA (purity 99%, diameter 100–250 nm) and PP pellets were purchased from Lotte Chemical Titan (M) Sdn Bhd, Malaysia (grade Titanpro 6331). Other than that, PMMA pellets were supplied by LG Chemical, South Korea and acetone was supplied by HmbG Chemical, Germany. All chemical and materials were used without any further purification.

Fabrication of PP/SiCNWs/PP Microwave Welded Sample

To fabricate PP substrates, hydraulic hot press machine (GoTech, Taiwan) was utilised to hot press PP pellets into PP sheet. After that, the PP sheets were cut into PP substrates using a customised cutter and hand press. Two types of PP substrates were prepared according to dimension stated in ASTM D3163 for single lap shear test and ASTM D790 for three-point bending test, respectively. Next, targeted area was marked on the PP substrate. Fig. 1 shows the dimension of targeted area for single lap shear test and three-point bending test, respectively.

For SiCNWs suspension, 0.75 wt% PMMA pellets were first dissolved in 10 mL acetone by magnetic stirrer. After that, SiCNWs powder was added into the PMMA solution and further mixed for 15 min followed by ultrasonication for 60 min. From preliminary study, the solid loading of SiCNWs suspension was fixed at 8.75 wt%. Due to the targeted area of PP substrates for three-point bending test is double to the targeted area of PP substrates for tensile test, therefore, 0.2 mL and 0.4 mL of well-dispersed SiCNWs suspensions were then drop-casted on the targeted area of PP substrate for single lap shear test and three-point bending test, respectively. The

SiCNWs coated PP substrate was dried on a hot plate to vaporise the acetone. Another plain PP substrate was placed on top of the SiCNWs coated PP substrate before subjecting to microwave irradiation.

From the preliminary studies, the microwave heating duration of 18 s is the optimum heating duration and hence, the sandwiched sample was subjected to microwave heating for 18 s to form welded joint. For sandwiched sample that was prepared for single lap shear test, two extra PP tabs were placed at the bottom and top side of the sandwiched sample to avoid unbalancing during microwave welding process, as shown in Fig. 2. Microwave welding was performed in a domestic microwave oven (Sharp R213CST, 2.45 GHz) without any further modification. For this domestic microwave oven, the microwave power level was designed at five different levels which is 80 W (Low), 240 W (Medium Low), 400 W (Medium), 560 W (Medium High) and 800 W (High). Therefore, in this study, the range of microwave power studied was limited to these levels. Besides, the sandwiched sample was pressed together by glass slide to exert predetermined clamping pressure on the samples during the microwave welding process and cooling process. Fig. 2 shows the setup of the microwave welding of sandwiched sample for single lap shear test in microwave oven. For the study of effect of microwave power, the microwave power studied was ranged from 80 W to 800 W while the microwave heating duration, solid loading of SiCNWs suspension and clamping pressure were kept constant at 18 s, 8.75 wt% and 3649.33 Pa, respectively. On the other hand, for the study of effect of clamping

pressure, the clamping pressure studied was ranged from 3649.33 Pa to 14597.31 Pa while the microwave heating duration, solid loading of SiCNWs suspension and microwave power were kept constant at 18 s, 8.75 wt% and 800 W. The clamping pressure used in this study can be denoted as P0, P1, P2, P3 and P4 for 0 Pa, 3649.33 Pa, 7298.65 Pa, 10947.98 Pa and 14597.31 Pa respectively.

Characterization

The morphology of SiCNWs was observed using field emission scanning electron microscopy (FESEM, LEO 1525). As the welded sample may detach or crack during the sectioning process, epoxy resin was used to mould the welded sample before sectioning the centre of welded sample. The moulded welded sample was sectioned using jigsaw and the thickness of sectioned moulded sample was set at 5 mm. After sectioning, the moulded cross-section sample was grinded and polished with various grit (up to grit 1200) of sandpaper. In order to study the cross-section microstructure of the welded joint, scanning electron microscopy (SEM, Hitachi TM-3000) was used to observe the cross section of the welded samples. A thin layer of platinum was coated on the polished moulded cross-section sample by sputter coater (JFC-1600 Auto Fine Coater) to prevent charging during SEM examination.

The tensile strength of welded sample was measured by single lap shear test using universal testing machine (UTM, Instron 5569). The tensile strength obtained represented the weld strength of the welded joint. Two PP alignment tabs were glued at the grip length of welded sample before subjected to testing as shown in Fig. 3. This is to eliminate the effect of out of plane bending moment and to ensure the uniformity of shear stress at the interface during testing. The welded sample was then clamped at the fixture and pulled apart at a constant crosshead speed of 1.27 mm/min and gauge length of 139.7 mm as stated in ASTM D3163.

The flexibility of welded sample was tested by three-point bending test using the same UTM. According to ASTM D790, the ratio of support span-to-depth was set at 16:1 for flatwise sample with thickness of 3.2 mm or less. As a result, support

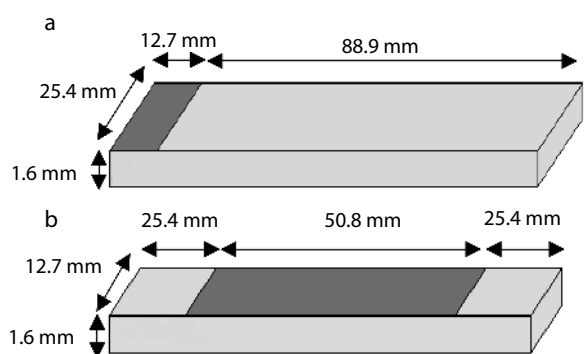


Fig. 1 Dimension of targeted area on PP substrate for (a) single lap shear test and (b) three-point bending test.

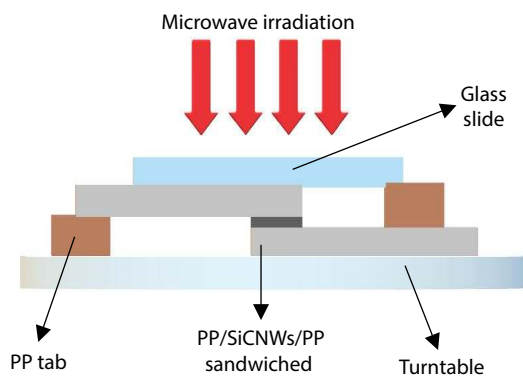


Fig. 2 Setup of single lap shear test sandwiched sample for microwave welding in microwave oven.

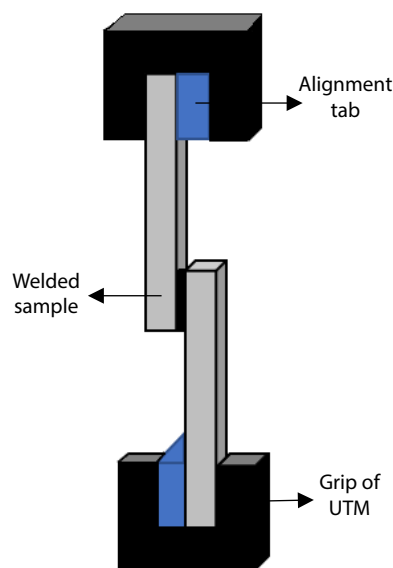


Fig. 3 Setup of welded sample at UTM for single lap shear test.

span used in this study was set at 51.2 mm. The welded sample was tested with a crosshead speed of 1.37 mm/min as calculated from the formula given in the ASTM standard.

RESULTS AND DISCUSSION

Morphology of SiCNWs

Fig. 4 shows the FESEM image of SiCNWs at magnification of 10k and 30k, respectively. Two types of structures which are straight whisker-like shape and entangled wire-like structure were observed. The diameters of SiCNWs range from 60 nm to 250 nm, as in Fig. 4(b). This observation is in line with the study of synthesis of SiCNWs using biomass cellulose char as carbon source reported by Omoriyekomwan *et al.* They reported that SiCNWs show different types of structures including straight rod-like and twisted wire-like structure.^[25] In another study, Shen *et al.* claimed that SiC with straight microstructure is the most promising microwave absorber compared to other microstructures such as nanobelt and nanocable for their high dielectric loss.^[26] As a result, SiCNWs was chosen as microwave susceptor in this work.

Effect of Microwave Power

Fig. 5 shows the tensile strength of welded joint subjected to various microwave power levels. The microwave heating duration, solid loading of SiCNWs and clamping pressure were fixed at 18 s, 8.75 wt% and 3649.33 Pa, respectively. When the sandwiched sample subjected to 80 W of microwave irradiation, no weld was formed and thus, no tensile strength value was obtained. The tensile strength increased drastically from 0.44 MPa to 1.86 MPa as microwave power increased from 240 W to 800 W, resulting in nearly 322% rise in tensile strength. Similar study by Sun *et al.* reported that a tensile strength of 1.81 MPa for the welded joint formed using 8.0 wt% CNTs suspension as

susceptor, 20 s as heating duration, 1000 W as microwave power and 15680 Pa as clamping pressure.^[9] In this study, a maximum tensile strength of 1.86 MPa can be achieved in 18 s when 800 W was employed, which indicates that in this study, a higher tensile strength can be obtained in a shorter heating duration. This result can be inferred from the fact that when microwave power is increased, more energy is absorbed by the SiCNWs, resulting in a higher heating rate which can reach the melting point of PP in a shorter time which allows the penetration of SiCNWs into the molten PP to form a nanocomposite, subsequently leads to a welded joint with improved tensile strength. Wise and Froment reported similar results when they studied the effect of microwave power on the acrylic welded joint using carbon loaded polyester tape as susceptor. They reported that higher microwave power reduces the time required to develop a fully welded joint due to higher heating rate of the susceptor.^[4]

The photographs of welded sample before and after subjecting to single lap shear test were shown in Fig. 6. After subjecting to microwave irradiation, no weld was observed in 80 W welded sample. Only a small welded area was observed for 240 W welded sample, in which most of the SiCNWs coated area remained unmelted. For sample subjected to 400 W, the welded area is larger compared to 240 W welded joint. It is believed that when the microwave power increased, the amount of microwave energy transferred to SiCNWs also increased, resulting in a higher heating rate. Higher heating rate leads to a shorter time required to reach the melting

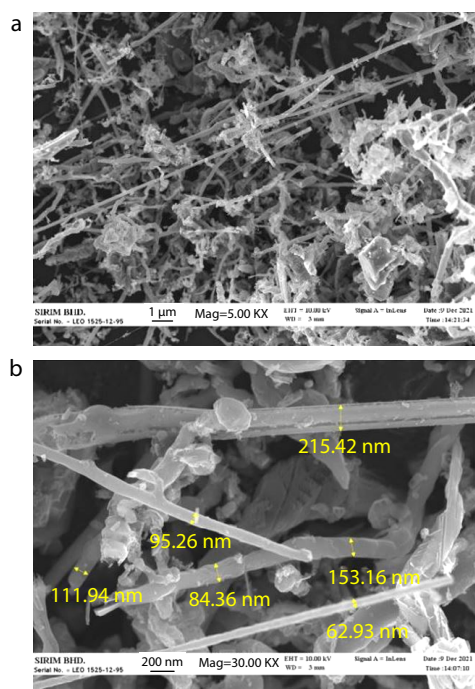


Fig. 4 FESEM images of SiCNWs at magnifications of (a) 10k and (b) 30k.

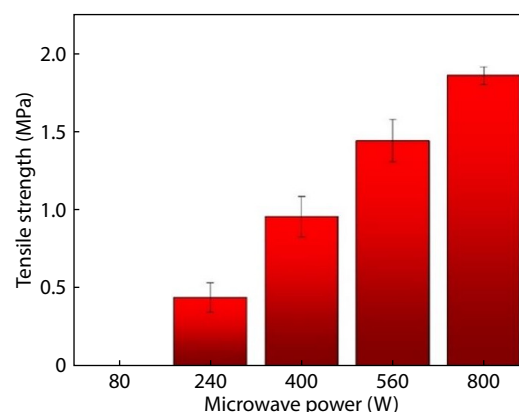


Fig. 5 Tensile strength of welded joint subjected to microwave power ranged from 80 W to 800 W.

Microwave power	(a) Before single lap shear test	(b) After single lap shear test
Low (80 W)	Not welded	
Medium low (240 W)	Small welded area	Adhesive failure
Medium (400 W)	Larger welded area	Adhesive failure
Medium low (560 W)		Substrate failure
High (800 W)		Substrate failure

Fig. 6 Welded sample subjected to different microwave powers (a) before and (b) after single lap shear test.

point of PP and allows chain entanglement across the interface of PP substrates, subsequently, a larger welded area was observed. However, adhesive failure was noticed for both 240 and 400 W welded sample, in which the welded joint detached after subjecting to single lap shear test. This can be attributed to the incomplete weld which is not strong enough to hold the welded PP substrates in place when single lap shear test is conducted. When the sandwiched sample was subjected to microwave irradiation of 560 and 800 W, the targeted areas were completely welded. Consequently, substrate failure was observed for both these welded joints. It is worth mentioning that the sudden fracture happened at the welded joint's edge, implying that the PP substrates are weaker than the welded joint. This might be because SiCNWs/PP nanocomposite was formed at the welded joint, which strengthened the welded joint and created a stress concentration at the edge of welded joint. As a result, the welded sample broke along the edge of welded joint rather than at the welded joint area. Both Wang *et al.* and Sun *et al.* reported similar observation when they subjected the microwave welded joint formed using carbon materials as susceptor to peeling test and tensile test respectively.^[8,10] They claimed that this type of fracture implies that the welded joint is stronger than the polymer substrate itself.

Microwave power is defined as the amount of microwave energy transferred per unit time. In the domestic microwave oven, the microwave power is varied by the percentage of operating time of microwave irradiation, which involves the magnetron and microwave energy pulsing on and off for pre-set duration. The microwave oven utilised in this study had an 800 W microwave power output when the operating time is 100%, which means that the magnetron worked continuously throughout the entire heating process. For 560, 400, 240 and 80 W, the percentage of operating time was pre-set at 70 %, 50 %, 30 % and 10 % by manufacturer, respectively. Based on the period of microwave irradiation, microwave power has a considerable impact on the rate of microwave energy transferred and the heating rate. As a whole, when low microwave power level was used, the amount of microwave energy transferred from magnetron was low, the amount of energy absorbed by SiCNWs is low and thus, resulting in a low heating rate and a longer duration is required to reach the melting point of PP. Therefore, when the heating duration is fixed, there might be insufficient time to reach the melting point of PP. In contrast, at high microwave power, the amount of microwave energy transferred from magnetron is high, resulting in rapid heating. Therefore, the time required to reach the melting point of PP is shorter. This explanation can be supported by the study conducted by Ke *et al.* in which they studied the effect of microwave power on the energy absorption performance of SiC particles.^[27] They examined the heating rate of SiC particles by determining the time required for the SiC particles to reach 200 °C. They found that the heating rate of SiC particles increased from 0.89 °C/s to 7.08 °C/s when the microwave power was increased from 300 W to 500 W. They claimed that when low microwave power was used, most of the microwave energy was lost during the dissipation process. Besides, they also claimed that the microwave electric field was intensified with the increase of microwave power, resulting in the absorption of higher amount of energy by SiC particles and thereby, increasing the

heating rates.

Furthermore, several studies also reported that the heating rate of microwave susceptor is significantly influenced by the microwave power. Zhao *et al.*, for example, studied the effect of microwave power level on the microwave drying rate of lignite.^[28] In their case, microwave drying rate can be said to be microwave heating rate because the direction of moisture migration is identical to direction of heat transferred from the core to the surface. They reported that the drying rate of lignite increased and time required to dry up the lignite decreased when the microwave power level increased from 500 W to 800 W. They claimed that this is due to the increase in electromagnetic intensity when high microwave power level was used, which resulted in an increasing microwave heating and drying rate.

In this study, no weld was formed when the sandwiched sample was subjected to low power of 80 W. As the operating time is short, the SiCNWs did not absorb sufficient energy from the magnetron. Subsequently, the heat released by SiCNWs did not reach the melting temperature of PP substrates and hence, no weld was formed. As the microwave power rose to 240 W and 400 W, the amount of energy generated by the magnetron increased as the operating time of magnetron increases. SiCNWs were able to absorb more energy from magnetron, resulting in higher heating rate to reach the melting point of surrounding PP substrates and therefore, welded joint was formed. However, the heat released is inadequate to fully melt the target area at both PP substrates. As a result, low tensile strength and detachment was observed when single lap shear test was conducted. When the microwave power was further increased to 560 and 800 W, the amount of energy absorbed by SiCNWs increased, which led to the melting of the SiCNWs coated PP at the entire target area and SiCNWs penetrated into the molten PP layer. Complete welded joint with SiCNWs/PP nanocomposite was formed. Subsequently, tensile strength of the welded sample was improved and strengthened welded joint was obtained.

Fig. 7 shows the modulus of elasticity of welded joint as a function of microwave power. It is interesting to note that the modulus of elasticity of the welded joint increases as the microwave power increases. When sandwiched sample was subjected to microwave irradiation of 80 W, the welded joint failed to form because the amount of energy transferred to SiCNWs was inadequate to reach the melting point of PP. Following that, the modulus of elasticity of welded joint subjected to 240 W attained 1.10 GPa, which increased steadily until it reached the highest modulus of elasticity of 2.35 GPa for 800 W welded joint. It shows an approximately 113.64% improvement in modulus of elasticity. One possible explanation is that when low microwave power (240 W and 400 W) was used, only thin molten layer was created and all the SiCNWs was seated in the thin molten layer which might result in agglomeration of SiCNWs at the welded joint. As microwave power increases, the SiCNWs are embedded deeper into the molten layer to form well dispersed SiCNWs that reinforced PP nanocomposite at the welded joint when the molten layer was cooled. This is because when the microwave power increases, the heating rate of SiCNWs increases, owing to the increasing amount of microwave energy emitted from the mag-

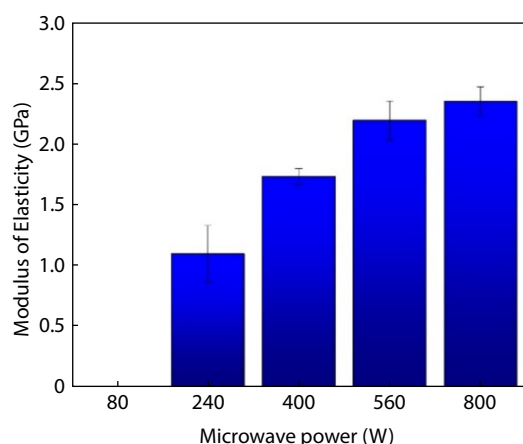


Fig. 7 Modulus of elasticity of welded joint subjected to different microwave powers.

netron, which results in the creation of a thicker molten layer that allows the embedment and dispersion of SiCNWs as well as formation of SiCNWs reinforced PP welded joint. Therefore, the modulus of elasticity and rigidity of welded joint improved when the microwave power increased. Mohit *et al.* reported similar results when they reinforced epoxy resin using aluminium and SiC nanoparticles (Al-SiCNPs) *via* ultrasonic assisted wet layup method.^[29] They recorded that the flexural modulus of the pure epoxy resin was 2.75 GPa and it improved to 3.76 GPa with the introduction of Al-SiCNPs into the epoxy resin.

On the other hand, the flexural strength of welded joint reduces from 35.16 MPa to 11.16 MPa when the microwave power increases from 240 W to 800 W, as shown in Fig. 8. Even though the inclusion of SiCNWs in PP matrix shows enhancement in the rigidity of welded joint, but it deteriorated the flexibility of the welded joint. This result is in line with the findings of Sanya *et al.*, who reported that the flexural strength of SiC reinforced epoxy decreases with the increase of volume fraction in SiC.^[30] They claimed that it is caused by the embrittlement of polymer matrix after inclusion of SiC particles. When low microwave power was used in this work, only a thin SiCNWs/PP nanocomposite welded joint layer was formed where most of the PP substrates remained their

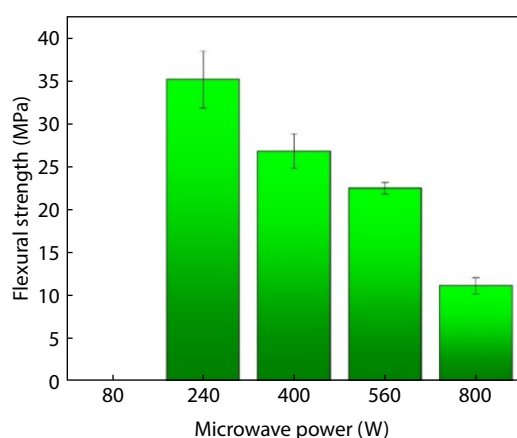


Fig. 8 Comparison of flexural strength of welded joint subjected to different microwave powers.

ductile nature. When force is applied to this welded joint, the SiCNWs in thin welded joint layer imparts negligible restriction to the mobility of polymer chain while retaining the high flexural strength of PP. Hence, the welded joint formed with low microwave power exhibits high flexural strength and a low modulus of elasticity. As the microwave power increased, the thickness of molten layer increased due to the higher heating rate. Consequently, the SiCNWs was incorporated deeper into the PP matrix and formed a thick and well-dispersed nanocomposite at the interface. Due to the presence of SiCNWs, the PP polymer chain cannot slide through each other when the forces are applied and therefore, resulted in welded joint with a higher modulus of elasticity but lower flexural strength.

In addition, the fracture conditions of the welded joint differed significantly after subjected to three-point bending test as shown in Fig. 9. The yellow box in Fig. 9 reveals the welded area and the fracture condition of the welded sample subjected to different microwave power. As expected, the sandwiched sample subjected to microwave radiation of 80 W was not successfully welded. Following that, when the microwave power increased, the welded area became larger until the whole targeted area was entirely welded when 560 W and 800 W was employed. As shown in Fig. 9, the welded joints formed by 240 and 400 W microwave radiation show similar failure condition in which the welded sample were bent and detached at the interface during testing. This type of failure may be attributed to the incomplete welded joint which failed to keep the PP substrates together when the sample was subjected to three-point bending test. In contrast, the welded joint formed using power of 560 and 800 W broke thoroughly at the welded joint without detachment. These fracture conditions are in line with the flexural strength and modulus of elasticity obtained by three-point bending test, in which 240 W and 400 W welded joints exhibit high flexural strength and low modulus of elasticity, which results in deflection occurring at the welded joint. However, 560 W and 800 W welded joints exhibit high modulus of elasticity and low flexural strength because of the thicker SiCNWs reinforced PP layer which consequently embrittled the welded joint.

The SEM images of cross-sectional microstructure of the

Microwave power	After three-point bending test
Low (80 W)	Not welded
Medium low (240 W)	
Medium (400 W)	
Medium high (560 W)	
High (800 W)	

Fig. 9 Fracture conditions of welded joint after subjected to three-point bending test.

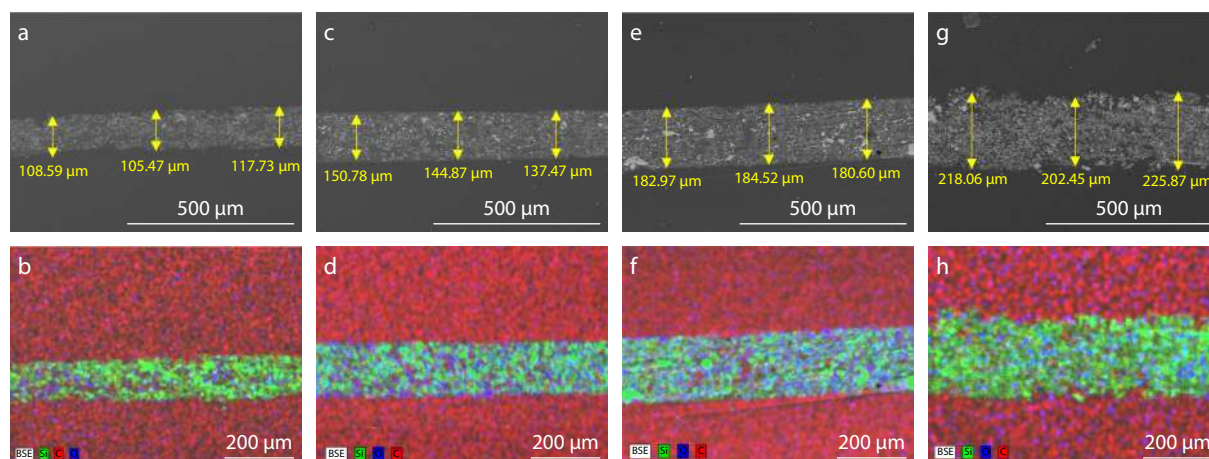


Fig. 10 Cross-sectional microstructure and EDX elemental mapping of the welded joint layer subjected to (a, b) 240 W, (c, d) 400 W, (e, f) 560 W and (g, h) 800 W microwave radiation at magnification 200 $\times$.

welded joint subjected to microwave of 240 W to 800 W are shown in Figs. 10(a), 10(c), 10(d) and 10(g). It can be observed that the thickness of the welded joint layer is uniform. The average thickness of welded joint layer subjected to different microwave power is shown in Table 1. From Table 1, the average thickness of the 240 W welded joint layer was 110.60 μm , and it increased to 215.46 μm when the microwave power increased to 800 W, which shows approximately 94.81% increment in the average thickness of welded joint layer. This increment can be attributed to the increasing energy absorbed by SiCNWs with the increase in microwave power. Subsequently, increased heat released by SiCNWs led to formation of thicker welded joint. When low microwave power, for example 240 W was used, the average off time of magnetron is high, in which relatively small amount of microwave energy was transferred to SiCNWs and a thin molten layer was generated upon the heat released by SiCNWs. The consequence was that SiCNWs was incorporated into the thin molten layer, which in turn resulted in low modulus and low tensile strength. On the contrary, thicker molten layer was formed when high microwave power was used, allowing SiCNWs to be embedded deeper into the molten layer due to emission of a relatively high amount of microwave energy when the average operating time of magnetron was increased. Following the solidification of molten layer, a thicker SiCNWs reinforced PP nanocomposite welded joint layer was formed at the welded joint. The formation of SiCNWs/PP nanocomposite with higher thickness is believed to contribute majorly to the enhancement of modulus of elasticity of the welded joint as in Fig. 7. Fig. 11 depicts the SEM micro-

graphs of welded joint layer at magnification of 1200 $\times$. These images show that SiCNWs was fully embedded into the PP matrix after solidification and formed a SiCNWs/PP nanocomposite at the welded joint layer.

Figs. 10(b), 10(d), 10(f) and 10(h) show the elemental area mapping of the welded joint layer at the interface of welded sample subjected to different microwave power. As observed in the EDX mapping image, the distribution of SiCNWs in the welded joint layer is uniform for all welded sample subjected to different microwave power. Besides, the overall structures of bulk PP for all welded sample subjected to different microwave power remained intact. This is because when the samples were subjected to microwave irradiation, only SiCNWs were able to absorb the microwave and heated up rapidly. The heat was then dissipated to the adjacent PP substrate and led to localised melting of adjacent PP interface. Besides, it can be noticed from Fig. 10 that the top and bottom side of the welded joint is PP without presence of the element of Si. Owing to the relatively low thermal conductivity of PP, the heating rate is low in the bulk PP compared to the PP interface. It is, however beneficial as the degradation of PP that is further away from the interface can be prevented due to low

Table 1 Average thickness of welded joint layer at interface subjected to different microwave power.

Microwave power (W)	Average thickness of welded joint layer at interface (μm)
80	Not welded
240	110.60
400	144.37
560	182.70
800	215.46

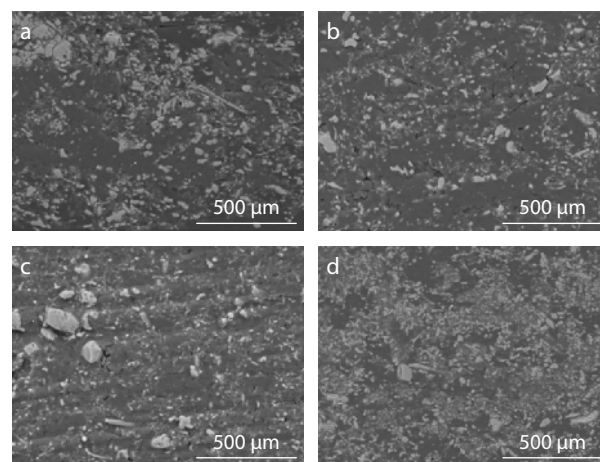


Fig. 11 Cross section microstructure of (a) 240 W, (b) 400 W, (c) 560 W and (d) 800 W welded joint at magnification of 1200 $\times$.

thermal conductivity of PP. The molten PP was formed due to the heat dissipated from SiCNWs and in the presence of clamping pressure, the molten PP filled into the gaps between SiCNWs and integrated into SiCNWs/PP nanocomposite at the interface of PP substrates after solidification. It is suggested that this is the main reason in which the silicon element was only detected at the welded joint layer due to the embedment of SiCNWs into the welded joint layer as shown in the EDX elemental mapping images in Fig. 10. Xie *et al.* reported a similar observation when they developed microwave welded joint using polyethylene (PE) as thermoplastic substrates and super-aligned CNTs film as microwave susceptor.^[11] They reported that uniform bonding was obtained after microwave welding and CNTs were well distributed at the interface of substrates as well as the overall structure of the PE remained its nature due to localised heating of CNTs. Besides, they further reported that the enhancement of bonding strength of the welded joint is attributed to the embedment of CNTs and intercalation of CNTs across the PE substrates.

Fig. 12 displays the fracture surfaces of welded joint exposed to various microwave power. There are several smooth areas in Figs. 12(a) and 12(b), which are the unmelted regions of the PP substrate. Furthermore, most of the SiCNWs were spread across the surface of PP substrates rather than being entirely incorporated into the PP matrix. This observation is consistent with those in Figs. 6 and 9, which indicates that low heating rates at low microwave power (240 W and 400 W) irradiation result in poor bonding between PP substrates. Furthermore, as can be seen in Figs. 12(a) and 12(b), at low microwave power, the SiCNWs were mostly not wetted by the PP substrate, they acted as two separate materials, as many gaps and hollow spaces were observed in between the interface of both materials thus contributed to low strength. In Fig. 12(c), the better wetting was observed, but partial SiCNWs still remained unwetted. The interface of welded joint became tougher as the microwave power increased to 800 W as demonstrated in Fig. 12(d). The PP was fully melted and was able to wet the SiCNWs as well as the gaps between the interface of both materials was not obvious to be seen. In this case, when force was applied to the welded joint, the stress was bore by the PP first which then transferred to SiCNWs, therefore higher load was required for the material failure.

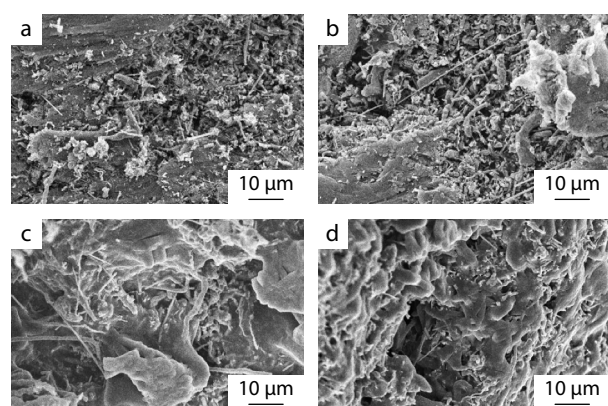


Fig. 12 Fracture surface of (a) 240 W, (b) 400 W, (c) 560 W and (d) 800 W welded joint.

Thus, higher strength was observed.

Effect of Clamping Pressure

Fig. 13 compares the tensile strength of welded joint prepared under different clamping pressure. The microwave heating duration, solid loading of SiCNWs and microwave power were fixed at 18 s, 8.75 wt% and 800 W. Welded joint formed using P0 demonstrated the lowest tensile strength of 0.75 MPa. This is because when no pressure was exerted on the sandwiched sample, there is limited contact between SiCNWs and PP substrates, which causes difficulty in heat transfer from SiCNWs to neighbouring PP substrates. At the same time, the chain mobility of PP was also low when the heat is insufficient to bring the PP substrate into molten state. Owing to these reasons, the welded joint exhibits low tensile strength. Choudhury and Debnath also stated that clamping pressure is necessary to develop a thermoplastic welded joint because clamping pressure enables good contact at the joint interface, which subsequently promotes heat conduction.^[31] Following that, the tensile strength increased slightly from 1.86 MPa to 2.21 MPa with the increase of clamping pressure from P1 to P3. It is thought that with the higher clamping pressure, the SiCNWs comes into close contact with the PP substrates, thus, enabling effective heat transfer to the neighbouring PP substrates and melted them. The pressure then forced the molten PP to intercalate across the interface and led to the development of welded joint with increased tensile strength after the molten PP was cooled. Wu *et al.* studied the microwave welding of PP substrates using MWCNTs/PP composite powder as susceptor.^[32] They reported similar results, such that the fracture load of the welded joint increased with the increasing of clamping pressure. They explained the increasing fracture load of their welded joint is due to the application of high clamping pressure which could enhance the flow of polymer into the MWCNTs/PP composite layer and the intercalation between PP substrates and MWCNTs/PP composite can be improved. Besides, it is worth mentioning that the strength of 2.21 MPa obtained in this study is slightly higher than the result that was reported by Sun *et al.* even though a smaller clamping pressure was used in this study. Sun *et al.* developed a welded joint by using PP as thermoplastic substrates and graphite powder as the susceptor and they obtained a maximum tensile strength of 2.09 MPa using a 78 kPa clamping pressure.^[8] This is in good agreement with Sun *et al.* which claimed that small clamping pressure is enough to achieve high strength welded joint provided that the microwave heating duration is sufficient to fully melt the PP substrate.^[9]

However, the tensile strength dropped to 1.62 MPa when the clamping pressure was further increased from P3 to P4. It is likely that deformation of PP substrates such as flashing and thinning happened when over-pressuring occurred at the welded joint. Subsequently, the tensile strength of welded joint was reduced. This is also in good accordance with the study conducted by Sun *et al.* in which the properties of welded joint may deteriorate when high pressure was exerted on the molten PP.^[9]

Figs. 14(a) and 14(b) show the photographs of the welded joint formed without clamping pressure and with clamping pressure (represented by P3), respectively. There appears to be a gap at the welded joint formed in the absence of clamp-

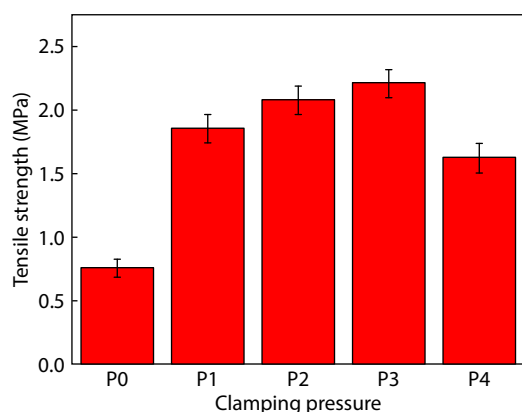


Fig. 13 Tensile strength of welded joint formed by various clamping pressure.

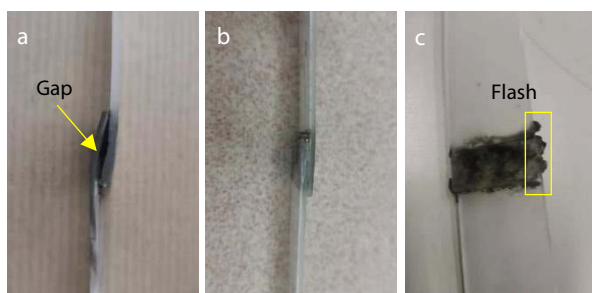


Fig. 14 Photograph of welded joint subjected to different clamping pressures: (a) P0 (without clamping pressure), (b) P3 (10947.98 Pa) and (c) P4 (14597.31 Pa).

ing pressure as in Fig. 14(a). This observation can be inferred to the minimal contact between the SiCNWs coated PP and coupled PP substrate when no pressure is applied, resulting in small welded area and presence of gap at the welded joint. On the other hand, with the presence of appropriate clamping pressure (P1 to P4), the welded joint was entirely welded without gaps due to the presence of clamping pressure which provided intimate contact between the substrates and facilitated the heat transfer process. Nevertheless, flashing of polymer at the welded joint was observed at the welded joint formed with clamping pressure P4, as shown in Fig. 14(c). It is believed that when P4 was used, over-pressuring happened at the welded joint in which the molten polymer was forced to spill out.

Because of the various welded joint conditions observed, the fractured mode of the welded joint was significantly affected after subjecting to single lap shear test. As indicated in Fig. 15(a), the welded joint formed in the absence of clamping pressure detached when tensile force was applied. Besides, it also shows an unheated zone at the targeted area. As previously stated, there is limited contact between the PP substrates, and it is believed that the unheated zone at the welded area represents the location where appropriate contact is lacking. Therefore, the welded joint only formed partially in the targeted area where the PP substrates came into contact, resulting in a welded joint of low strength and occurrence of detachment when tensile force was applied. Fig. 15(b) shows the photograph of welded joint formed in the presence of clamping pressure after subjecting to single lap

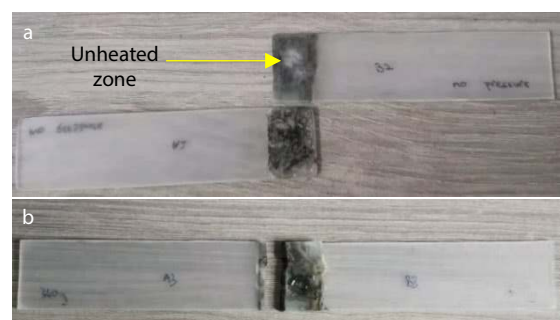


Fig. 15 Fracture condition of welded joint prepared in the (a) absence of clamping pressure and (b) presence of P3 (10947.98 Pa) clamping pressure.

shear test. Substrate failure where the welded sample fractured at the edge of the welded joint was observed for all the welded joints produced in the presence of clamping pressure. Substrate failure occurs when the strength of the PP substrates is weaker than that of the welded joint. This can be attributed to the incorporation of SiCNWs into PP substrates, which resulted in the strengthened welded joint due to the formation of SiCNWs/PP nanocomposites at their interface. Similar observation was reported by Sun *et al.* when they prepared microwave welded PP using graphite as susceptor.^[8] They claimed that the formation of graphite/PP composite at the welded joint is the main reason of the improved strength of welded joint.

During microwave welding, SiCNWs absorbed microwave energy and converted it into heat to melt the neighbouring PP substrates. In the presence of clamping pressure, the SiCNWs embedded into the molten PP and SiCNWs/PP nanocomposite was formed at the interface of welded joint after the welded joint cooled and solidified. So, in this work, SiCNWs not only plays the role of microwave susceptor, but also as nanofiller for the formation of nanocomposite. In general, SiCNWs is a ceramic material with high modulus when used as a filler in composites. Fig. 16 shows the modulus of elasticity of the welded joint as a function of clamping pressure. Obviously, the modulus of elasticity increased drastically from 0.95 GPa to 2.36 GPa when the clamping pressure was raised from P0 to P1. In the absence of clamping pressure, it is believed that SiCNWs cannot penetrate deeply into the molten PP substrates, hence, resulting in the low modulus at the welded joint. Increasing the clamping pressure from P1 to P4 enhanced the modulus of elasticity slightly by 24.26%. A maximum modulus of elasticity of 2.93 GPa was attained by the welded joint formed using P4 clamping pressure. This implies that with the increase of clamping pressure, SiCNWs were forced to incorporate deeper into the melted PP substrates and formed nanocomposite at the welded joint with increasing thickness. Hence, the modulus of elasticity of welded joint was improved because SiCNWs restricted the movement of polymer chains of PP substrates. It is worth mentioning that the modulus of welded joint increased while the tensile strength decreased when the clamping pressure increased from P3 to P4. This is because when clamping pressure P4 was used, the molten PP was forced to spill out from the targeted area and this caused thinning of the welded joint layer. Therefore, only small force was needed to break the welded

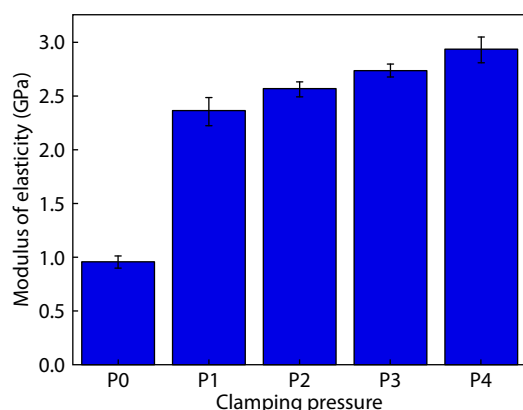


Fig. 16 Modulus of elasticity of microwave welded joint subjected to different clamping pressures.

joint. According to Eq. (1),^[33] the tensile strength is directly proportional to the tensile force, and hence, the tensile strength of P4 welded joint reduced. On the contrary, modulus is inversely proportional to the thickness of sample as shown in Eq. (2).^[34] Therefore, the modulus of welded joint increased when clamping pressure P4 was exerted due to the reduction of overall thickness of welded joint caused by flashing.

$$\sigma = \frac{F}{A} \quad (1)$$

$$E = \frac{L^3 F}{4bh^3 y} \quad (2)$$

where σ is tensile strength, F is force applied, A is overlap area, L is the length of span, b is the width of the welded sample, h is the thickness of the welded sample, and y is the distance covered by load F .

On the other hand, the flexural strength of the welded joint formed by using different clamping pressure was shown in Fig. 17. Overall, the flexural strength decreases gradually with the increase of clamping pressure except for the welded joint formed in the absence of clamping pressure. Lowest flexural strength of 5.21 MPa was obtained for the welded joint formed without clamping pressure and it is believed that this low flexural strength is due to occurrence of detachment when the testing was conducted. The flexural strength then decreased from 11.18 MPa to 7.18 MPa when the clamping pressure was increased from P1 to P4. It exhibits an inverse relationship with modulus of elasticity. One possible explanation is that when the clamping pressure increases, SiCNWs were forced to penetrate deeper into the molten layer and a larger depth of PP substrates was filled with SiCNWs which subsequently formed a thicker nanocomposite welded joint layer. The inclusion of high fracture toughness SiCNWs into PP has substantial impact on the polymer chain relaxation. When force is applied to the welded joint, SiCNWs restricted the mobility of polymer chain by interlocking the polymer chain and as a result, low flexural strength but high modulus of elasticity was obtained. This observation is in line with the results reported by Erklığ *et al.* in their studies of the mechanical properties of various inorganic filler filled polyester resin.^[35] One of the fillers studied by them was SiC micro-particles. They reported that the flexural strength and flexural

modulus of polyester increased with the introduction of SiC micro-particles. Besides, the flexural modulus of SiC micro-particles filled polyester increases with the increasing solid loading of SiC micro-particles, but at the same time, the flexural strength decreases.

Fig. 18 illustrates the fracture condition of P0 and P3 welded joint after three-point bending test. Fig. 18 shows that the fracture conditions of the welded joint prepared in the absence and in the presence of clamping pressure after subjecting to three-point bending test were totally different. Fig. 18(a) shows that the welded joint formed in the absence of clamping pressure detached during the testing. Moreover, it can also be seen that only a few spots in the targeted area melted, leaving large part of SiCNWs coated PP substrate remained unwelded due to the poor contact between PP substrates, resulting in detachment when testing was conducted, and hence, low flexural strength and low modulus of elasticity. On the other hand, all of the welded joints formed in the presence of clamping pressure are fully welded and they show similar fracture condition in which the welded joints break at the center of welded joint. Therefore, it is worth mentioning that pure PP substrate only bent after subjected to the three-point bending test and it is believed that it is due to its high ductility and flexibility. As mentioned above, the introduction of rigid SiCNWs in the presence of clamping

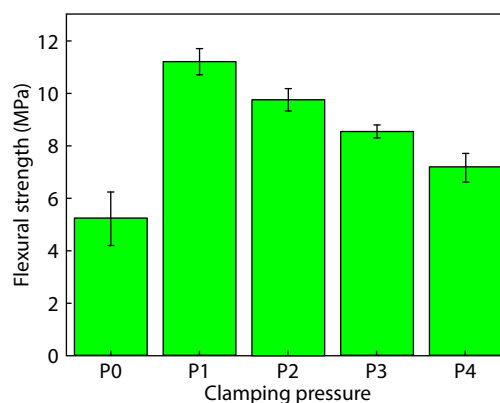


Fig. 17 Flexural strength of welded joint as a function of clamping pressure.

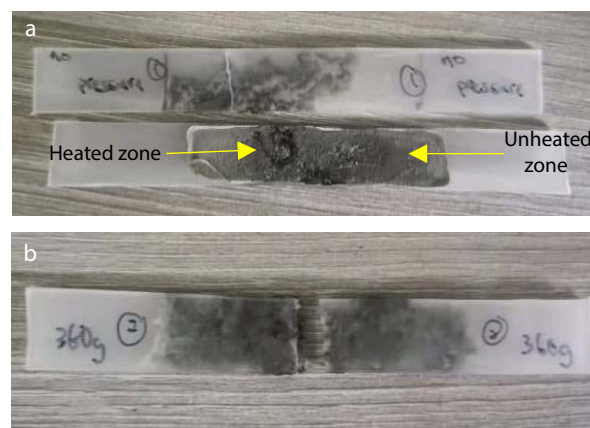


Fig. 18 Fracture conditions of the welded joint prepared in the (a) absence of clamping pressure and (b) presence of clamping pressure of P3 after subjecting to three-point bending test.

pressure enhanced the stiffness and rigidity of the welded joint, but at the same time, it embrittled the welded joint. Consequently, the welded joint formed in the presence of clamping pressure fully broke at the welded area when three-point bending test was conducted.

The cross-sectional microstructure and EDX elemental mapping of the welded joint formed in the absence and presence of increasing clamping pressure was presented in Fig. 19. Figs. 19(a) and 20(a) show the SEM image of welded joint formed in the absence of clamping pressure at magnification 200 $\times$ and 1200 $\times$, respectively. It can be seen that gaps are found along the welded joint layer with only a few welded spots. This is in good agreement with the poor mechanical properties of the welded joint due to poor contact between PP substrates in the absence of clamping pressure and large

part of the targeted area remained unmelted and unwelded. Besides, the welded joint formed in the absence of clamping pressure has the lowest welded joint layer thickness among the welded samples in which it only attained average thickness of 97.25 μm . EDX elemental mapping in Fig. 19(b) also shows the inhomogeneous distribution of SiCNWs at the welded joint layer. Without clamping pressure, intercalation of the molten PP only occurred at certain spots of the targeted area and the SiCNWs were only embedded into the molten PP of certain spots, resulting in low tensile strength, low modulus of elasticity and low flexural strength. Figs. 19(c), 19(e), 19(g) and 19(i) and Figs. 20(b), 20(c), 20(d) and 20(e) show the cross-sectional microstructures of the welded joint formed in the presence of clamping pressure P1 to P4 at 200 $\times$ and 1200 $\times$, respectively. It can be observed that the SiCNWs were

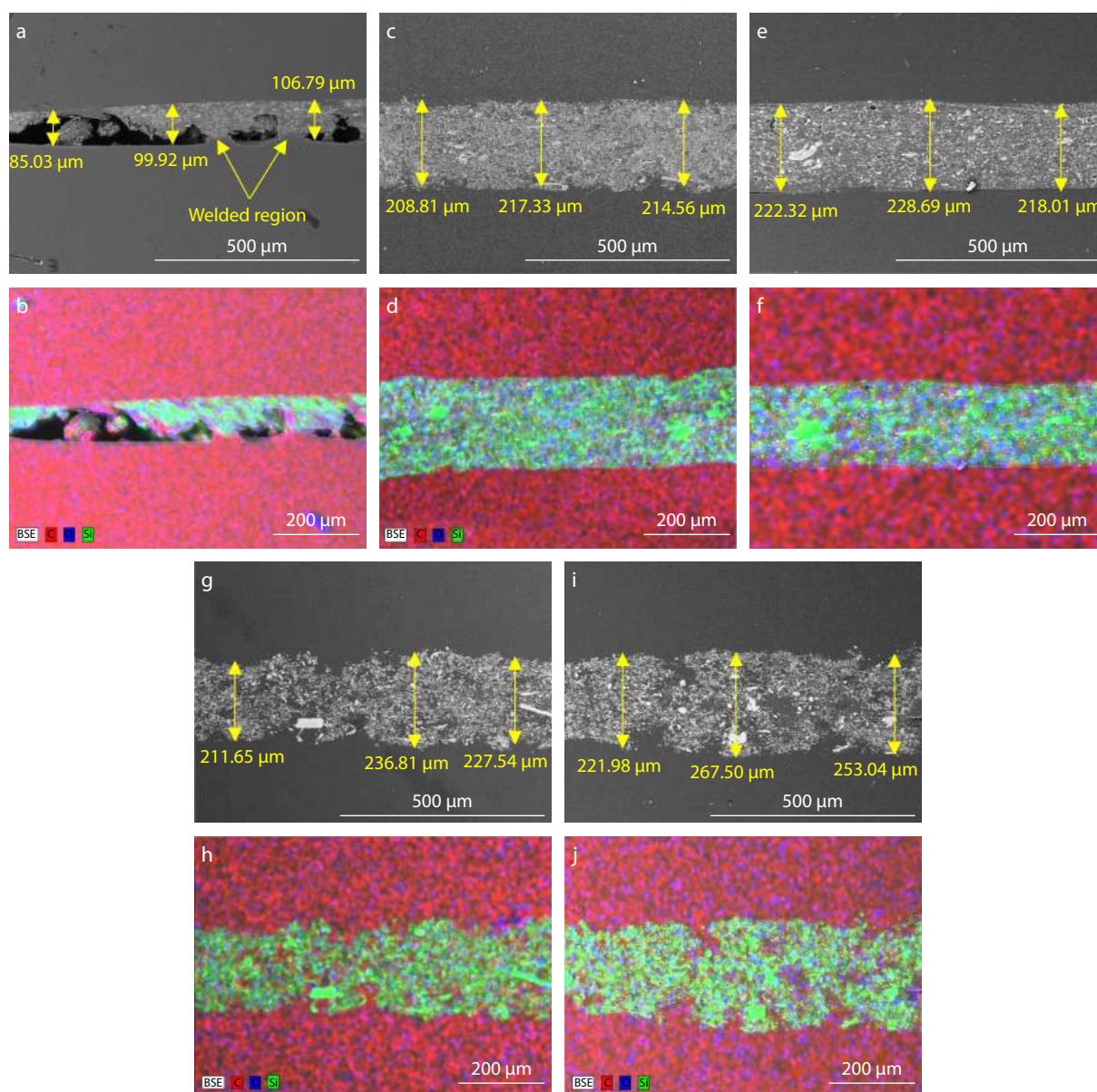


Fig. 19 Cross-sectional microstructure and EDX elemental mapping of (a, b) P0, (c, d) P1, (e, f) P2, (g, h) P3 and (i, j) P4 welded joint at magnification 200 $\times$.

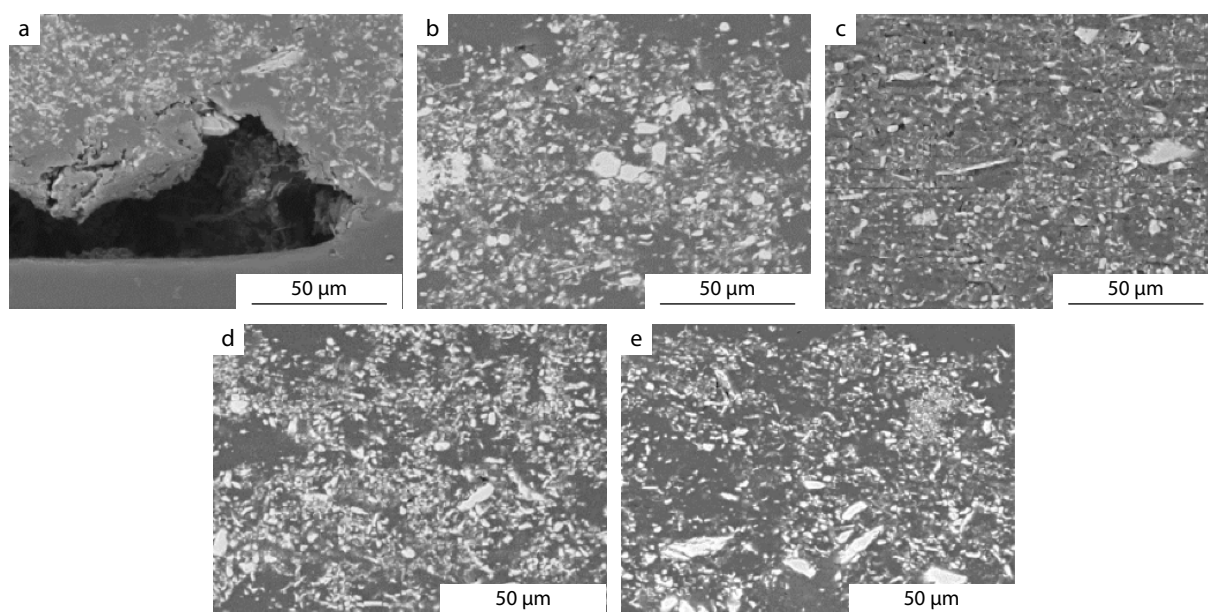


Fig. 20 SEM micrograph of welded joint formed with (a) no pressure, (b) P1, (c) P2, (d) P3 and (e) P4 at magnification of 1200 $\times$.

distributed uniformly in all welded joint formed in the presence of clamping pressure P1 to P4. Fig. 19(d), 19(f), 19(h) and 19(j) show the EDX elemental mapping of the welded joint formed in the presence of clamping pressure P1 to P4, respectively. The EDX elemental mapping confirms that for all welded joints formed in the presence of clamping pressure P1 to P4, SiCNWs were homogeneously embedded into the welded joint layer while the top and bottom side of PP substrates that are further away from the interface remained unchanged after subjecting to microwave welding process. This is because PP are microwave transparent materials in which the microwave propagated through it without any interaction. Furthermore, due to low thermal conductivity of PP, only the interface of PP was melted by the heat released from SiCNWs. As a result, the overall structure of PP substrates remained unchanged after subjecting to microwave welding. Similar observation was reported by Wang *et al.* in which they studied microwave welding of multiwalled carbon nanotube (MWCNTs) into poly(ethylene terephthalate) (PET) substrates.^[10] They reported that MWCNTs was completely intercalated into PET after short microwave irradiation duration. Besides, they claimed that the overall structure of bulk PET remained unchanged after microwave welding is due to the thermal boundary resistance between MWCNTs and PET polymer, in which the thermal conductivity of MWCNTs is much larger compared to PET, resulting in low thermal heating rate at PET side.

Table 2 compares the average thickness of welded joint layer of welded joint formed in the presence of clamping pressure P0 to P4. It can be seen that P1 welded joint exhibits a low welded joint layer thickness of 213.57 μm . As the clamping pressure increased to P4, the average thickness of the welded joint layer at interface increased steadily to 247.51 μm by 15.89%. It is believed that the presence of higher clamping pressure can promote the intercalation of molten PP between the substrates. As a result, thicker molten layer was formed and SiCNWs were allowed to deep-seat into the mol-

Table 2 Average thickness of welded joint layer formed with various clamping pressure.

Clamping pressure (Pa)	Average thickness of welded joint layer at interface (μm)
P0	97.25
P1	213.57
P2	219.67
P3	223.01
P4	247.51

ten layer, as shown in Fig. 19, which led to the increase in modulus of elasticity of the welded joint.

Furthermore, it is observed from Fig. 19(b) to Fig. 19(e) that the distribution of SiCNWs in welded joint formed using higher clamping pressure is less dense. This is because at low clamping pressure, only a thin molten layer was created at the interface and all the deposited SiCNWs were penetrated into the thin molten layer and resulted in a dense welded joint. As the clamping pressure increases, a thicker molten PP layer was formed and SiCNWs dispersed more loosely in the molten layer, which resulted in a less dense joint layer. With the increasing average thickness of welded joint layer and constant amount of SiCNWs, the density of SiCNWs in joint layer decreases with the increasing clamping pressure.

Fracture surface of the welded joint formed without clamping pressure was shown in Fig. 21(a). The SiCNWs were partially wetted by the PP substrate, which had one end embedded into the PP substrate and the other end dangling between the interface. The dangling end of SiCNWs is thought to be the point where SiCNWs and PP substrate do not make contact. The welded sample was not able to bear the load evenly when load was applied due to the weak welded joint and resulting in the lowest tensile, modulus and flexural strength. Figs. 21(b), 21(c), 21(d) and 21(e) depict the fracture surface of the welded joint formed with clamping pressure P1, P2, P3 and P4, respectively. It can be seen that

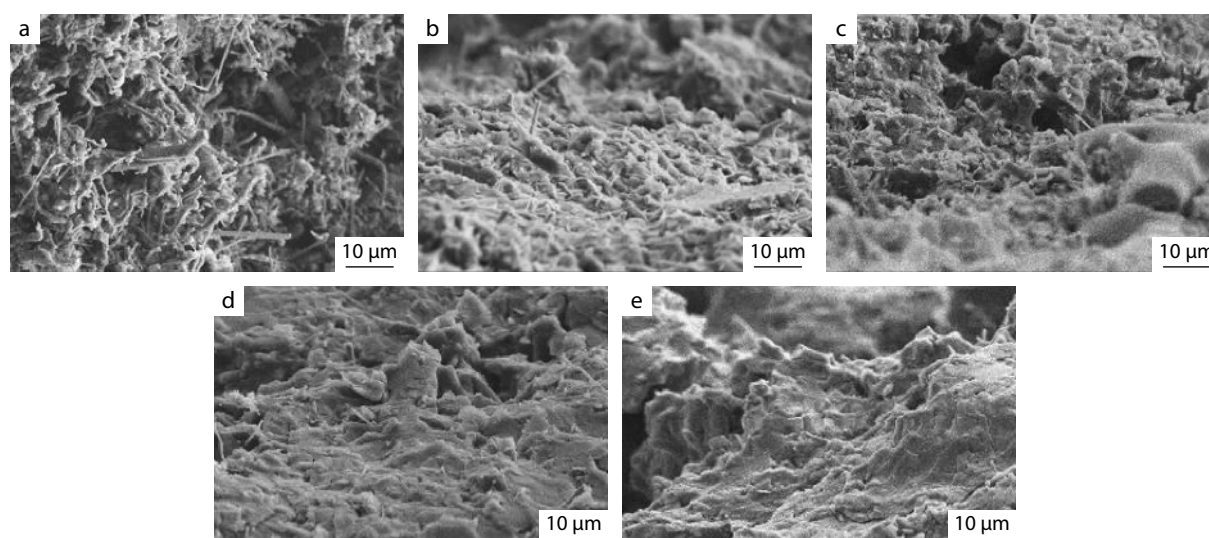


Fig. 21 Fracture surface of the welded joint subjected to clamping pressure: (a) P0, (b) P1, (c) P2, (d) P3 and (e) P4.

there were still some unembedded SiCNWs into the PP matrix when clamping pressure P1 was exerted, but not as much as compared to P0, as shown in Fig. 21(b) which contributes to increase of tensile and flexural properties. Following that, most of the SiCNWs was thoroughly embedded into the PP matrix as the clamping pressure rose from P1 to P4, and unembedded SiCNWs were hardly seen at the fracture surface. This is because, with the exception of the tensile strength of welded joint formed with clamping pressure P4, high clamping pressure can drive the SiCNWs to fully incorporate into the molten PP. More molten PP flowed and wetted the SiCNWs, leading to smoother fractured surface which indicated that more PP covered the SiCNWs. However, high clamping pressure causes the molten PP to overflow from the targeted area as can be seen in Fig. 14. This explained the lowest tensile strength that was observed for P4 sample as compared to P1, P2 and P3 samples. Yet, it is interesting to note that P4 welded joint still exhibited higher tensile and flexural properties as compared to P0 welded joint. Therefore, it can be concluded that clamping pressure has contributed to better filler-matrix interaction and thus improved the mechanical properties.

Formation Mechanism of SiCNWs Reinforced PP Welded Joint

SiC is a dielectric material that is microwave sensitive due to its high permittivity and intrinsic electric dipolar polarisation. Moreover, SiCNWs is notable for its exceptional microwave absorption due to its larger surface-to-volume ratio compared to bulk SiC particles and hence, SiCNWs was chosen as the microwave susceptor for the microwave welding of thermoplastic in this study.^[36,37] When SiCNWs were exposed to microwave radiation, dipoles were induced inside SiCNWs when the microwave's electric field interacted with SiCNWs.^[31] Because of its low magnetic properties and conductivity, Shen *et al.* claimed that the microwave absorption of SiCNWs mostly depends on dipolar polarisation.^[26] When no electric field is applied to SiCNWs, the dipoles in SiCNWs are disordered and leads to a zero net dipole moment. This is due to the fact that the vector sum of dipole moments equals to zero

since they cancelled each other out when all the dipoles are in random positions. On the contrary, the change in dipole moment resulted in dipolar polarisation. Generally, dipole moment was created when these dipoles absorbed the microwave energy, rearranged themselves along the direction of the alternating electric field when exposed to microwave radiation, and thus, resulting in dipolar polarisation.^[38] When the frequency of electric field alternates, the polarizability of dipole cannot be maintained and hence, resulted in dielectric loss.^[39] Furthermore, friction was created during the dipole reorientation because the dipoles continually rubbed against one another. Dielectric heating/microwave heating occurred as a result of the frictional loss in the form of heat.^[26,31,38]

Basically, most of the polymers such as PP in this study are microwave transparent materials, which means that microwave transmits through most polymers without interacting with them.^[40] In this case, microwave susceptor with high dielectric loss properties must be included at the interface of polymers for successful microwave welding.^[41] In this study, PP was used as the polymer substrate and SiCNWs was coated on the PP substrates as a microwave susceptor due to its outstanding microwave absorption performance. Fig. 22 depicts the formation mechanism of SiCNWs reinforced PP welded joint during microwave welding. Before the sandwiched sample was exposed to microwave irradiation, a microwave transparent weight block such as a glass slide was used to provide intimate contact as well as to exert pressure with high targeted area, as shown in Fig. 22(a). Due to its large penetration depth, PP substrates did not experience rise in temperature when the sandwiched sample was exposed to microwave irradiation. Microwave energy was transmitted through PP substrates and absorbed by one of the SiCNWs coated PP substrates. After absorbing microwave energy, the dipoles in SiCNWs gained energy and began to rearrange themselves in the direction of alternating electric field, which led into the formation of dipole moment and friction. As a result, energy was lost in the form of thermal energy. The generated heat was transferred to the neighbouring PP substrates, which melted them when the temperature reached the melting point of PP. Simultaneously, as illustrated in Fig. 22(b), the

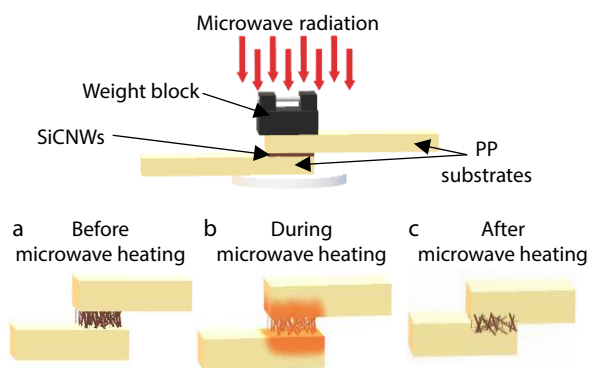


Fig. 22 Formation mechanism of SiCNWs reinforced PP welded joint via microwave welding.

clamping pressure forced the intercalation and chain entanglement of PP across the interface of the substrates as well as the incorporation of SiCNWs into molten PP. Following the removal of microwave radiation, the molten PP cooled, resolidified and consolidated as a whole to form a SiCNWs reinforced PP welded joint, as shown in Fig. 22(c). In brief, SiCNWs was used not only as a microwave susceptor in this study, but also as a nanofiller in connecting and reinforcing the microwave welded joint.

In general, microwave power can be defined as the rate at which microwave energy is transferred. Therefore, the amount of microwave energy absorbed by SiCNWs is different for different microwave power and has considerable impact on the mechanical properties of the welded joint. In fact, the microwave power level does not affect the intensity of the microwave radiation produced from magnetron, but it does regulate the amount of energy transferred to the SiCNWs by manipulating the operating time of the magnetron. Fig. 23 shows three distinct welded joint conditions subjected to low, ideal and high microwave power. As can be seen in Fig. 23(a), only few spots of the targeted area were melted and a thin molten layer was formed when low microwave power was employed. This is because the magnetron off time is longer than its operating time, the amount of energy transferred to SiCNWs is low, and the heat released by SiCNWs is insufficient to fully melt the adjacent PP substrates. Besides, as only a thin molten layer of PP was produced, SiCNWs were only allowed to be embedded into the thin molten layer to form thin SiCNWs/PP composite and agglomeration of SiCNWs may occur. As a result, a weak welded joint was formed at low microwave power. In other words, a completely welded joint

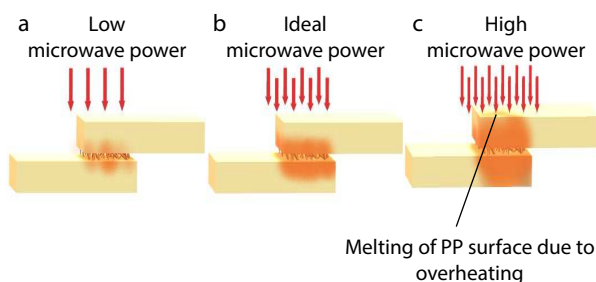


Fig. 23 Conditions of welded joint interface under different microwave powers.

may be formed with low microwave power but it may need a longer duration for SiCNWs to absorb sufficient microwave energy and be heated up to reach the melting point of PP. The ratio of operating time-off time of magnetron rises as the microwave power increases, resulting in a thicker molten layer of PP due to greater amount of microwave energy transferred and absorbed by SiCNWs. Meanwhile, when ideal microwave power was used, the entire targeted area was melted and all SiCNWs were embedded into the molten PP layer as shown in Fig. 23(b), resulting in a complete welded joint. Lastly, when high microwave power was used, the rate of microwave energy transfer was rapid, which may cause the SiCNWs to get heated up in a short period of time. Although it can shorten the processing time, high microwave power, on the other hand, may cause overheating at PP surface because the amount of heat released by SiCNWs is excessive and may be transferred to the surface of PP in a short period of time, as shown in Fig. 23(c). Subsequently, the strength of welded joint is reduced due to the formation of defects such as void at the PP substrate. In short, microwave power level can significantly affect the heating rate of SiCNWs and hence, it must be properly controlled in order to develop a complete welded joint without imperfection.

In addition to microwave power, clamping pressure also plays an essential role in determining the properties of a microwave welded joint. Fig. 24 shows the schematic representation of welded joint formed without clamping pressure, with ideal clamping pressure and with excessive clamping pressure. Clamping pressure is important in providing intimate contact between SiCNWs and PP substrates. Besides, it also plays a role in forcing the occurrence of polymer chain entanglement of the molten PP at the interface as well as the embedment of SiCNWs into molten PP. As can be seen in Fig. 24(a), in the absence of clamping pressure, gap may form at the interface of welded joint. A possible reason is that the heat released by SiCNWs was not transferred effectively to the adjacent PP substrates when they were not in close contact. Only certain area of the targeted area where SiCNWs and PP substrates come into contact were heated, melted and welded. To avoid this problem, a microwave transparent weight block was used to exert clamping pressure on the welded joint. Fig. 24(b) shows the condition of welded joint formed in the presence of appropriate clamping pressure. With appropriate clamping pressure, the molten PP was forced to flow across their interface and resulted in chain entanglement. Concurrently, SiCNWs was forced to incorporate into the mol-

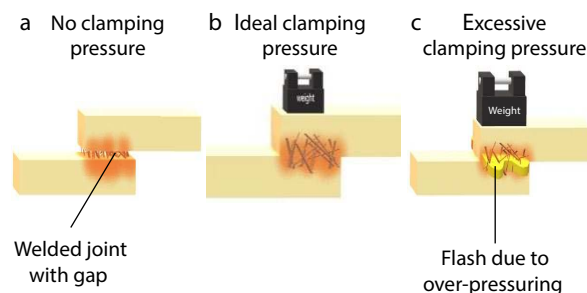


Fig. 24 Conditions of welded joint interface under different clamping pressures.

ten PP and hence, resulting in a strengthened welded joint after the molten PP was cooled. Nevertheless, if the clamping pressure is further increased, the welded joint may be over-pressed. Excessive clamping pressure may cause the molten PP to flow out of targeted area, resulting in the formation of a thin molten layer called flash at the edge of the welded joint as illustrated in Fig. 24(c). As a result, the mechanical properties of welded joint will deteriorate.

CONCLUSIONS

In summary, this study makes use of the dielectric heating principle by irradiating SiCNWs with microwave radiation to join thermoplastic PP substrates. Upon microwave radiation, SiCNWs not only served as microwave susceptor to absorb microwave energy and heat up rapidly to melt the surrounding PP substrates, at the same time, SiCNWs also served as a reinforcing agent in strengthening the PP substrates. After the molten PP was cooled, both PP substrates were joined together and SiCNWs/PP nanocomposite was formed at welded joint. The tensile strength and modulus of elasticity increased as a function of microwave power in this study because higher amount of energy was transferred to SiCNWs when a higher power level was used. Besides, the thicker PP molten layer allows SiCNWs to be embedded deeper into the PP substrates which resulted in high modulus of elasticity but low flexural strength. In the study of clamping pressure, it was found that the welded joints formed in the presence of clamping pressure have considerably high tensile strength, flexural strength and modulus of elasticity compared to the welded joint formed in the absence of clamping pressure. Furthermore, the tensile strength increased as the clamping pressure increased from P1 to P3. However, the tensile strength dropped when the clamping pressure was further increased from P3 to P4 due to flashing of molten PP at the welded joint caused by over-pressuring. Although the modulus of elasticity of welded joint increased as the clamping pressure increased, higher clamping pressure reduces the flexibility of the welded joint. This study proposed a welding technique which offers a cost-effective and time-efficient method in joining engineering polymers. It can be applied on parts with complex geometry where most of the conventional welding methods cannot.

NOTES

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