LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
LUT School of Energy Systems
LUT Mechanical Engineering

Himal Gurung

Impact of Different Polymer Wires on the Properties of Hot Gas Welded Wood Plastic Composites

Examiner(s): Professor Timo Kärki
D. Sc. (Tech.) Anna Keskisaari

ABSTRACT

Lappeenranta University of Technology
LUT School of Energy Systems
LUT Mechanical Engineering

Himal Gurung

Impact of Different Polymer Wires on the Properties of Hot Gas Welded Wood Plastic Composites

Master's thesis

Year of completion 2018

80 pages, 53 figures, 10 tables

Examiners: Professor Timo Kärki
D. Sc. (Tech.) Anna Keskisaari

Keywords: Wood plastic composites, filler wires, hot gas welding, WPC, tensile strength

Today's world is industrializing and heading towards development at a fast pace. Easiness of a life is the main motto of this generation. In order to provide maximum benefits plus fulfilling demands, day by day many new products are being manufactured. Many new raw materials have been building up and many cases they have already replaced the old raw materials to lower the price, giving more reliability, durability to the products. In a similar way, new composite materials have been made to enhance the material properties. Among them, Wood Plastic Composite (WPC) is the one.

Wood plastic composite is a mixture of wood flour and plastic fibers. It provides better properties than wood and plastic alone. For instance, wood plastic can be molded easily to any desired shape, but wood cannot be molded.

The main target of this thesis was to analyze and compare the tensile strength of welded wood plastic composites with non-welded wood plastic composites. Different filler wires using the hot gas welding procedure. Wood plastic composites with 70% High Density Polyethylene (HDPE) and 60% HDPE were adopted and filler wires like: commercial PP, commercial PE, filament extruded polyethylene (PE) containing 10% cellulose, filament extruded polypropylene (PP) containing 10% cellulose and filler wire same as base materials.

Different filler wires played a vital role in weld strength. Filler wires needed to be of the same composition as of base material to provide better weld quality. Furthermore, the result showed that weld strength increases as increasing in plastic content in wood plastic composites.

ACKNOWLEDGEMENTS

I would like to express my gratitude to prof. Timo Kärki and my supervisor Anna Keskisaari for providing me a chance to do my master’s thesis.

I sincerely thank my parents and sisters for trusting and supporting me in every step of my life. I might not be able to achieve this success without their love, support and care. I also wish to deep appreciation to LUT for providing me a perfect environment to learn and explore new things.

Finally, I also thank to all my teachers who always helped me to show a good path and encourage me to achieve my goals.

Himal Gurung

Lappeenranta 26.11.2018

Table of Contents

ABBREVIATIONS

ABS	Acrylonitrile butadiene styrene
EG	Ethylene glycol
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
PA	Polyamide
PC	Polycarbonate
PE	Polyethylene
PETE	Polyethylene terephthalate
PMMA	Polymethyl methacrylate
PP	Polypropylene
PPO	Polyphenylene
PS	Polystyrene
PTFE	Polytetrafluoroethylene
PVC	Polyvinyl Cholride
SEM	Scanning Electron Microscopy
SPI	Society of the Plastic Industry
TPA	Terephthalic acid
WPC	Wood Plastic Composite

.

1 INTRODUCTION

Wood Plastic Composites (WPCs) are newly developed composite materials which are mainly a combination of wood fibers with polymers either with thermosetting or thermoplastic. WPCs have very good strength/weight and stiffness/weight ratio hence enabling them to be a perfect material for the application in decking, in automobile companies, in furniture industry, in numerous technical applications. In 2012, the production of WPC worldwide was 2.43 million tons whereas a volume of 260,000 tons in Europe alone. (Friedrich and Luible 2016, p. 1143.)

Moreover, plastics are made from chemical raw materials known as monomers. A monomer is reacted with other monomer molecules and form a long chain with repeating units, which is referred as polymers. For instance, ethylene is reacted with other ethylene molecule forming a polymer polyethylene. In a similar way, polypropylene is made from propylene monomer. (Grewell, Benatar and Park 2003, p.3.)

The main target of this research work is to utilize hot gas mechanism along with different filler wires to identify the weldability of WPC. Moreover, best suitable filler wire to join the specific WPC would be identified. As said earlier, hot gas welding method will be used for this research work. Hot gas welding is solely used to weld thermoplastics where the stream of heated gas is passed to the weld joints so that the filler wire or welding rod and the welding surface can be melted. Filler wires with different compositions will be used and their effect on the welded joints will be analyzed. Hence, making a good filler wire to weld WPC with different recycled materials.

1.1 Plastics

Plastics are a very long chain molecule of macromolecules. The process of forming a polymer by long chain with monomers is called polymerization. The typical example of ethylene molecule is shown in Figure 1, the double bond in carbon atoms of ethylene allowing the creation of many ethylene hence forming a polyethylene (Goodship 2007, p.12).

$$CH_2CH_2CH_2CH_2CH_2CH_2$$

Figure 1. Polyethylene molecule (Goodship 2007, p. 12).

Although there is some distinct between plastics and polymers but often they are taken as similar. Polymers are a form of pure material made by the polymerization process having a long chain of molecules and when the additives are added the term is called plastics. Additives are applied for various reasons like: antistatic purposes, fillers, coupling agents, flame retardants, lubrications, stabilizers etc. (Crawford 2002, p. 3.)

Nowadays, plastics have replaced many materials like wood, cermics in various applications because of their many useful properties, comparatively low cost, low densities, good corrosion resistance, excellent thermal and electric insulation and easiness of manufacturing. The main drawbacks of plastic materials are low strength and elastic modulus thus making them softer than metals (John 1983, p. 231.)

Polymers are categorized into two groups: thermoplastics and thermosets. Some examples of thermoplastic types are Polyethylene (PE), Polyvinyl chloride (PVC), Polystyrene (PS), nylon, cellulose acetate, Polypropylene (PP), Polycarbonate (PC) and Polymethyl methacrylate (PMMA). Thermoplastics are generally divided into 2 sub classes: Amorphous and Semi-crystalline thermoplastics. Normally, amorphous thermoplastics are brittle in nature but lacks brittleness above the glass transition temperature (T_g). Amorphous thermoplastics refer to randomly or unordered coiled molecules as shown in Figure 2 (Grewell, Benatar and Park 2003, p.5). According to the figure, heating the amorphous thermoplastics lead to the mobility of chain segments thus forming a longer distance to entangled chains. The common examples of this type of polymers are PVC, PS, Polymethyl

methacrylate (PMMA), Polycarbonate (PC), Acrylonitrile-butadiene-styrene (ABS) and Polyphenylene (PPO) (Crawford 2002, p. 4).
Some applications of amorphous thermoplastics are: power tools, corrosion resistant pipes, aircraft canopies etc.

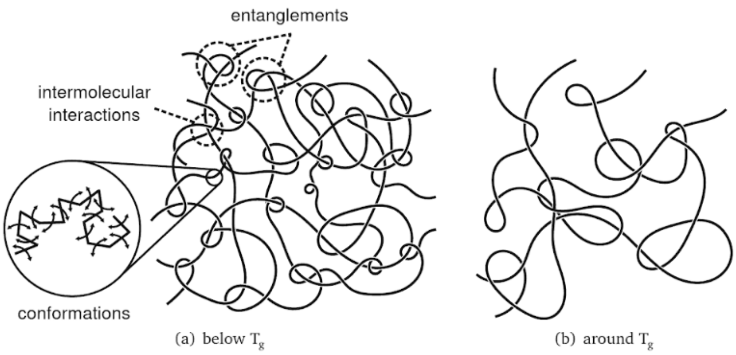

Figure 2. Entangled amorphous thermoplastics (Hempel 2016).

Semi-crystalline thermoplastics are named as they have some portion of structures in crystalline morphology and remaining structures have highly ordered and compact in nature. Unlike amorphous thermoplastics, semi-crystalline thermoplastics can form three dimensional ordered arrays. This type of thermoplastics is good in aircraft interiors and ship/submarine applications. Semi-crystalline thermoplastics are well known for flame resistance, good toughness, excellent mechanical properties at elevated temperature and having good moisture absorption resistant. General molecular structure or semi-crystalline thermoplastic is shown in Figure 3.

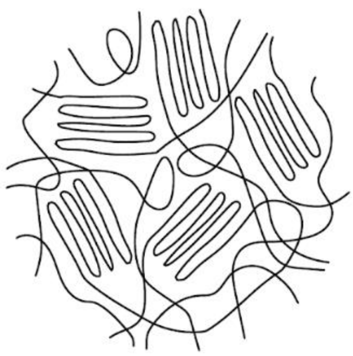

Figure 3. Molecular structure of semi-crystalline thermoplastics (Ropers 2016, p.6.)

While the world is on advanced development pace, many products are manufacturing day by day for more easiness of human lives. This is the main reason for the utilization of more materials. More demand enhances the consumption of more materials. Thus, companies should focus on recycling the used materials rather than using virgin materials, which helps in maintaining the green environment plus less consumption of virgin materials.

There are seven different plastic types based on their recyclability as shown in Figure 4 and their main application fields.

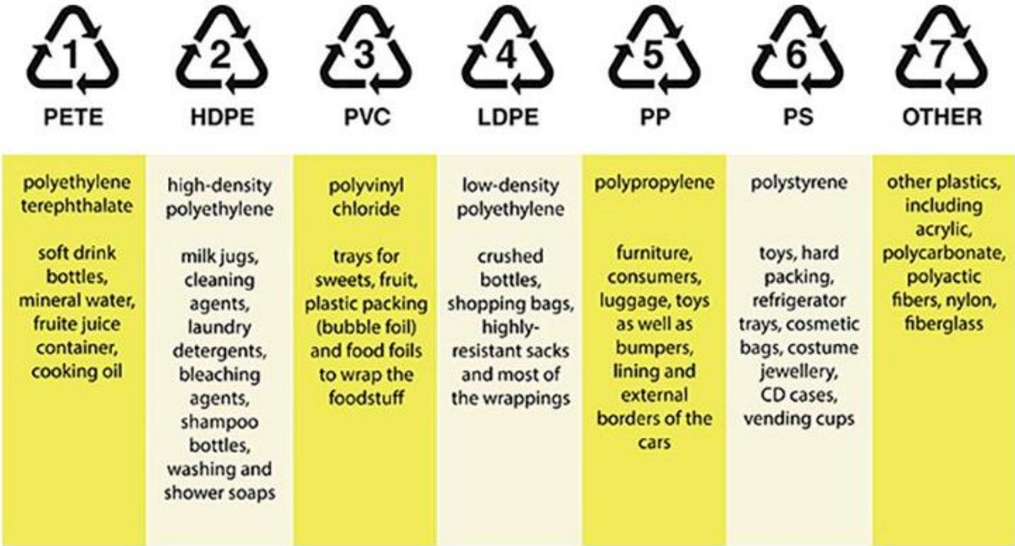

Figure 4. Classification of plastics based on recyclability (Seaman 2012).

Polyethylene terephthalate or commonly known as PET or PETE is a type of polyester in the textile company and the most useful thermoplastic polyesters because of its cheapness, light weight, easily available and easy to process and manufacturing. Figure 5 shows the basic way of producing PETE. It involves the polycondensation process of terephthalic acid (TPA) and ethylene glycol (EG) and two reactions. Among one of them, bis (hydroxyethyl) terephthalate or prepolymer is formed by esterification reaction of TPA with EG. And in another reaction, so called transesterification reaction where bis (hydroxyethyl) terephthalate is formed by the reaction of dimethyl terephthalate with ethylene glycol.

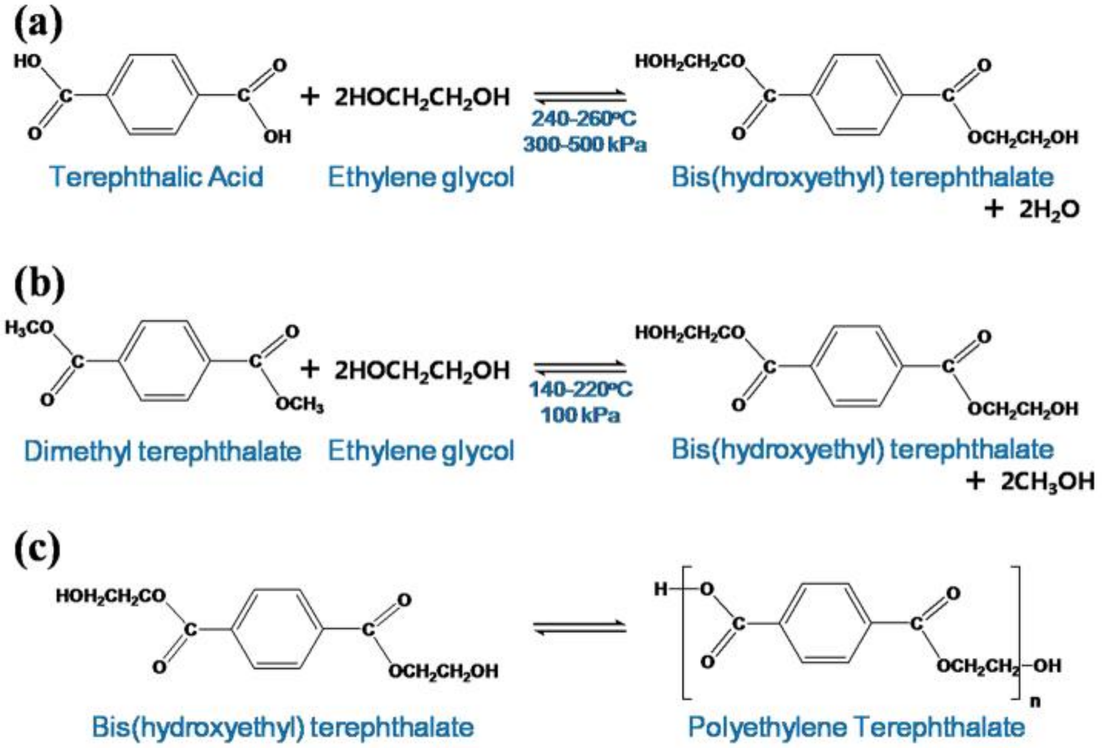

Figure 5. PETE manufacturing process: (a) esterification, (b) transesterification and (c) final condensation reactions (Park and Kim 2014, p. 4).

PETE is a type of non-degradable plastic type in the natural stage thus causes environmental pollution if disposed. Decomposing PETE is very complex and expensive procedure plus causes toxic gases. Thus, the recycling of PETE is a good option economically and environmentally. And it is obvious that excessive use of PETE products causes waste management problems leading to environmental pollution. And there are many studies going to reuse PETE more efficiently (Park and Kim 2014).

High density polyethylene (HDPE) is a type of thermoplastics that are basically embed with fibers to enhance mechanical properties. Glass and carbon fibers are the most commonly used reinforcing materials for HDPE (Teodorescu-Draghicescu et al. 2018). HDPE has chemically close in structure with pure polyethylene (Peacock 2000, p. 2). It is a mostly used plastic material in industrial applications because of its high tensile strength properties, impact strength, and excellent machinability. Their main areas are in making butter tubs, water pipes, garbage containers, huge amount of toys are made by HDPE etc (Seretis, Manolakos and Provatidis 2018, p. 81.)

Polyvinyl Chloride (PVC) is one of the thermoplastics types and are made from ethylene and anhydrous hydrochloric acid. It has high modulus of elasticity plus high tensile strength. It is mainly suitable for making power cables because its excellent thermal, mechanical as well as dielectric properties (Gouda et al. 2014, p. 1). Other applications of PVC include water piping, video-discs, construction, credit cards, packaging etc. In 2002 alone, nearly 27 million metric tons of PVC was produced with a value of 59 billion pounds (Sass, Castleman and Wallinga 2005). The main thing to about PVC is that it contains about 57% chlorine by weight that generates chlorinated hydrocarbons and thermally decomposes into hydrochloric acid, which is corrosive and toxic (Yoskioka et al. 2009, p. 489).

Low density polyethylene (LDPE) contains massive combination of branches that cripples the crystallinity process which results in having low density. Thus, this polymer is named as low density polyethylene (Peacock 2000, p. 2). It is mostly popular packaging material for varieties of products like: foods, milk, agricultural products, electronics etc. Nearly 35% of plastic materials made in developed countries are used for packaging purposes (Veethahavya et al. 2016, p.710). Moreover, they are also applicable in various industrial and medical uses. They are an example of classic cable material (Shen et al. 2018, p.75). They are partially crystalline solid in structure having a crystallinity of 50-60% range which gives valuable properties like: good tensile strength, opacity, rigidity, chemical resistance and good tear strength (Saki 2015, p.191).

Polypropylene (PP) is one of the mostly used polyolefin polymers with numerous positives aspects like: good corrosion resistance, strength, good weather resistance, low weight and cheap. Due to its good mechanical properties and low weight, it is ideal material in automotive construction (Ngaowthong, Rungsardthong and Siengchin, 2016). Polypropylene is one of the lightest thermoplastics thus the products are light in weight. Moreover, it has excellent strength-to-weight ratio and more rigid/stiff as compared to polyolefins. Polypropylene has the highest melting temperature than all other available thermoplastics of about 160°-170°C (Maier and Calafut 1998, p. 1). Thus, almost all types welding process for thermoplastic is suitable for welding polypropylene.

The common polypropylene forming process is shown in Figure 6 below where the PP is formed by the polymerization of propylene by Ziegal-Natta polymerization or by using metallocene catalysis polymerization process (TutorVista 2018).

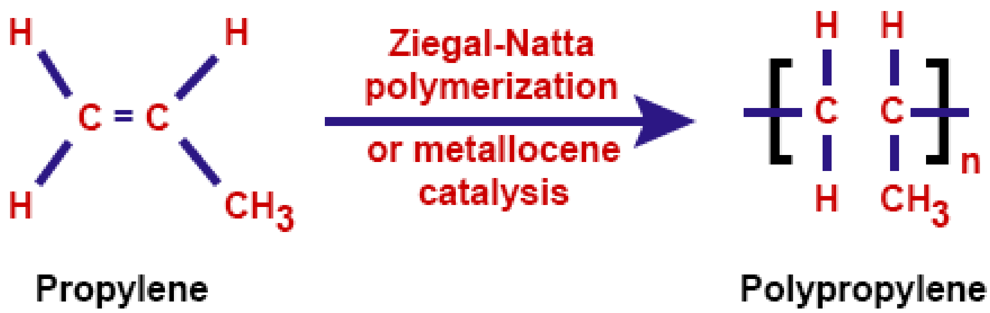

Figure 6. Polymerization of propylene to polypropylene (TutorVista 2018).

Furthermore, polypropylene is classified into two classes as isotactic and atactic propylene. Isotactic propylene polymer chain represents all the methyl groups at same side as of backbone chain as shown in Figure 7 (Kim and Somorjai 2006).

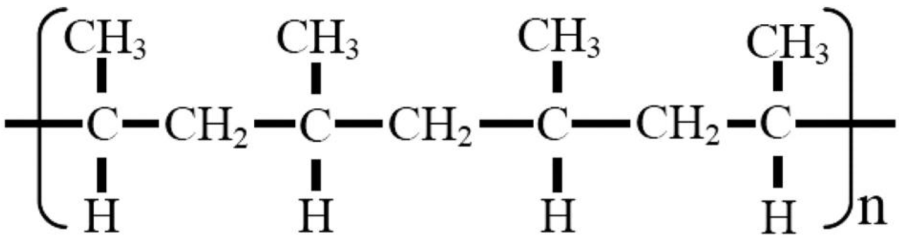

Figure 7. Structure of isotactic propylene (Kim and Somorjai 2006).

In contrast to isotactic propylene, atactic propylene type has alternative sharing or distribution of methyl group at backbone carbon atoms. Some typical structure of isotactic propylene is depicted in Figure 8.

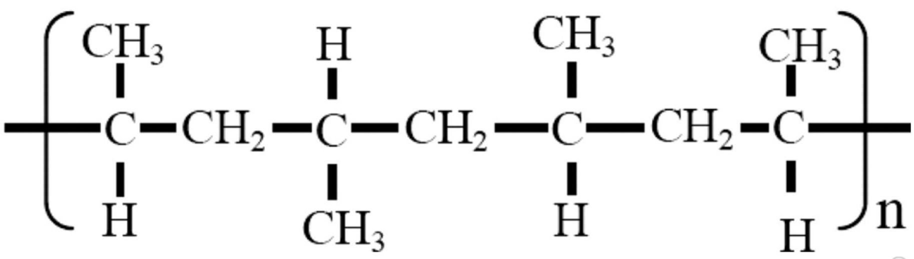

Figure 8. Structure of atactic propylene (Kim and Somorjai 2006)

1.2 Recycled Plastics and Their Use

The use of plastics products is increasing every year. But the use of virgin plastics need more money on oil extraction, polymer manufacturing and increases more environmental pollutions by large amount of CO_2 emission (Rajendran et al 2012, p. 131). Figure 9 shows the consumption chart of different plastic types in Europe context.

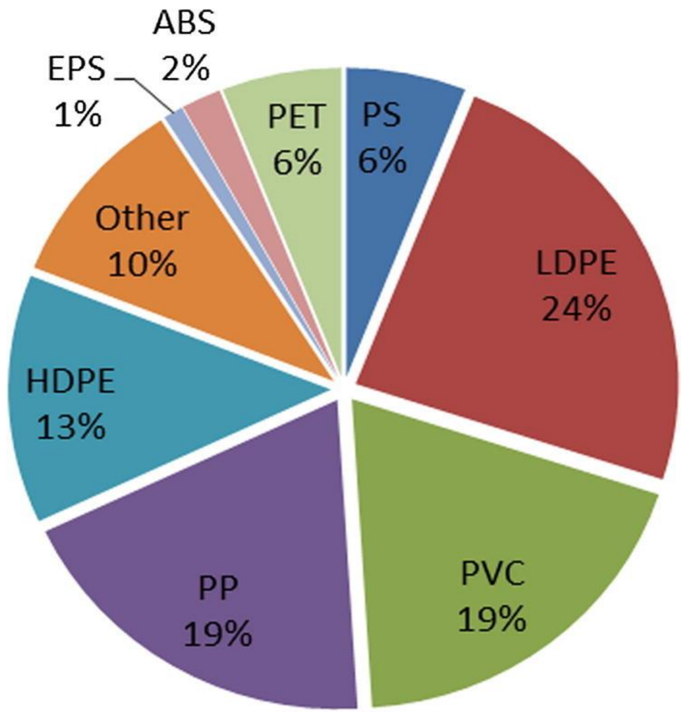

Figure 9. Different plastic types consumption in Europe (Ragaert, Delva and Van Geem 2017, p. 43.)

As explained earlier, various plastic grades are available and have their own applications. Thermoplastics melt and flow when heat is supplied and solidify after they cooled. Thus, they can be recycled by remelting process. Table 1 shows the lifecycle of different thermoplastics with the applications.

Table 1. Lifecycle of different thermoplastics with applications (Goodship 2007, p. 16).

Thermoplastics	Lifecycle
HDPE	Packaging: about 2 years Pipes: about 30 years
LDPE	Packaging: about 2 years
PP	Packaging: about 2 years Battery casings: about 10 years
PS	Packaging: about 5 years Cassettes: about 10 years
PA	Bearings, gears, bolts, fishing lines: 10 years
PET	Carbonated drink bottles: about 5 years
PVC	Food packaging, shoes: about 5 years

1.3 Wood Plastic Composites

Wood plastic composite (WPC) is a composite material made by the combination of wood wastes like wood sawdust or wood flour and a recycled plastic (Kim and Pal 2011, p.1). They are also considered as eco-friendly and have the potential to replace natural wood. Therefore, their demand and use is increasing every year. In the year 2015 only, the production of WPC reached about 2,7 kilo tons and it is predicted to increase. The main applications of WPC include window fitting, fences, furniture, door flame etc. (Koay et al. 2018).

After analyzing the positive and negative aspects of wood and plastic components, the WPCs are developed as shown in Figure 10. The composition of wood sawdust and plastic results in better quality of the final product. Presence of wood increases the stiffness of a product than using of only polymers. Moreover, plastic components give the good compression properties and covers the hydrophilic nature of woods resulting give the good resistance to thickness swelling and rotting (Das, Sarmah and Bhattacharya 2015, p.330).

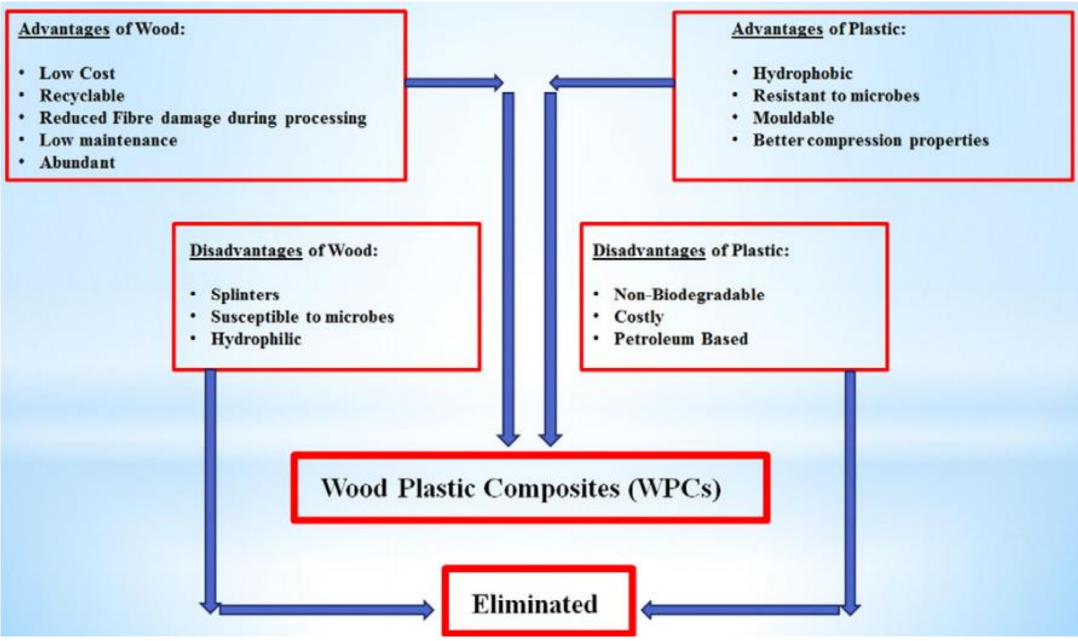

Figure 10. Reasons of developing WPCs (Das, Sarmah and Bhattacharya 2015, p. 330.)

1.3.1 Components of WPC

WPC is composed of grinded sawdust/wood flour and plastics. In case of plastics, either thermoplastics or thermosets can be utilized. As mentioned earlier, thermosets like phenolics and epoxies can be molded again for only once, but thermoplastics used in WPCs like: PE, PP, PVC, ABS and PS can be reused after re-melting. Even though additives are used in small portions they are necessary for providing necessary stiffness, rigidity and good stability against heat and light. Coupling agents play a vital role in providing mechanical properties by achieving polarity thus helping in building strong chemical bonding. They also help in enhancing attachment between resin and fibers to increase tensile and flexural strength plus reduces the rate of moisture absorption. Moreover, lubricants are necessary to give smooth surface, increasing extrusion rate and to reduce friction (Atozplastics 2003). The components of WPC are shown in Figure 11. The important reasons to use thermoplastics in WPC are:

- Reduce prices
- Excellent mechanical properties
- Low melting temperature
- Low processing temperature for both wood flour (maximum 200°C) and plastics.

Figure 11. Components of WPC (Polymaterial 2013).

1.3.2 WPC manufacturing process

Manufacturing process of WPC mainly consists of three major steps 1) processing of wood flour 2) compounding 3) molding of the materials by injection molding or extrusion or by compression molding (Hietala 2011, p. 3).

At the beginning, mixing of wood flour with melted thermoplastics takes place, which is generally known as compounding process. This process is done in the blending equipment. There are mainly two types of blending equipment, a single screw and twin-screw extruder (Andre 2011, p. 17).

In single screw extruder, screw helps in delivering the materials to be mixed. Screw is generally wound about the shaft as shown in Figure 12. Shearing forces are applied between the screw and barrel. The major working steps of single screw extruder includes: the raw materials are first fed into the hopper which after melted also mixed by the head provided by the heaters. Then mixed materials are injected into the die forming extruded or compounding parts. (Andre 2011, p. 19).

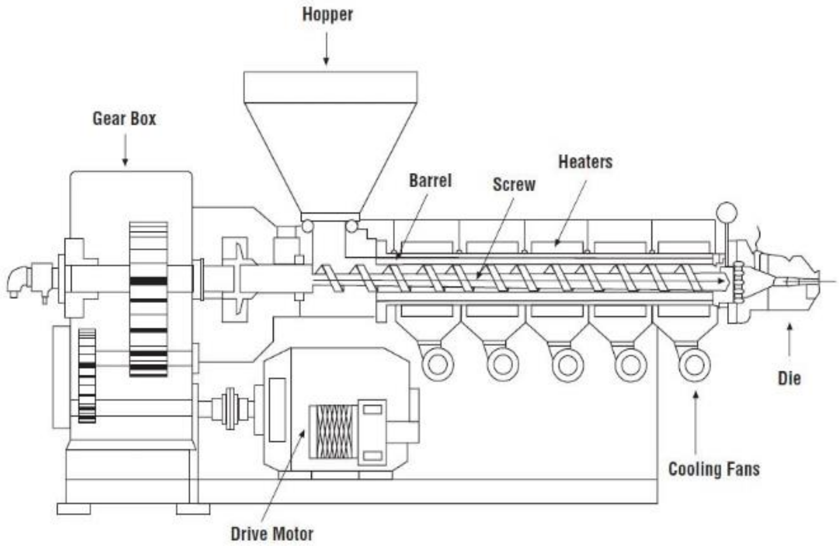

Figure 12. Single screw extruder (AZoM 2017).

Twin screw extruder provides better mixing of raw materials thus it is used when the single screw extruder doesn’t meet the desired degree of mixed products. It is done due to the intermeshing actions which is also known as the displacement of mixed raw materials from one screw to another resulting the better mixing proportions. There are further two types of twin screw extruder: counter-rotating screws and co-rotating screws. Co-rotating screws provide better mixing plus lower dwelling time as compared to counter-rotating screws. (Andre 2011, p. 19). Twin screw extruder is illustrated in Figure 13.

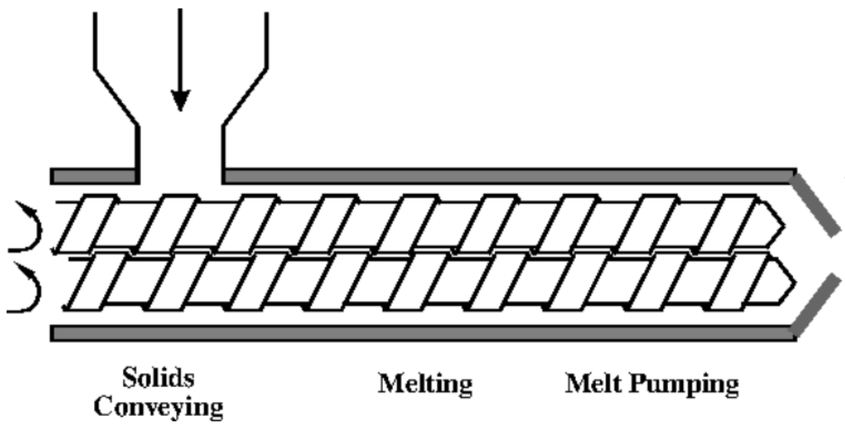

Figure 13. Twin screw extruder (Patil et al. 2005, p. 2).

1.3.3 Demand of WPC

Wood plastic composite is getting more popular day by day because of its numerous benefits. Europe alone occupies the third-largest demand for WPC. They are mainly used to make furniture, household appliances, technical parts, consumer products. It is estimated that from 2018-2026, the demand of WPC to rise with 13.12% Compound Annual Growth Rate (CAGR), producing about $812.3 million by its end. Figure 14 shows the market of WPC in million around Europe (Inkwood Research 2017).

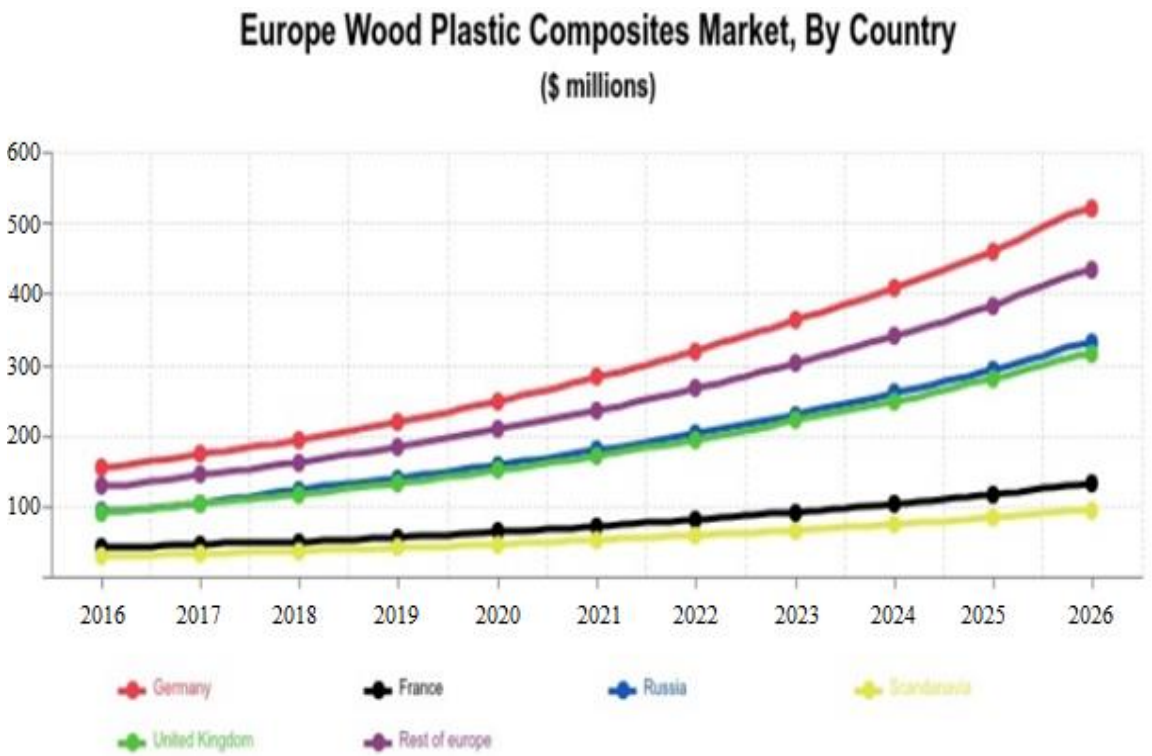

Figure 14. Demand of WPC in Europe (Inkwood Research 2017).

Germany is the major WPC users in the world as they manufacture automobiles. In U.K., using of recycled plastics plus wood is gaining popular, leading to the excessive use of WPC in numerous purposes. Among other European countries like Austria, Switzerland, Portugal and Spain are the major consumers of various thermoplastics like: PE and PVC (Inkwood Research 2017).

Moreover, Figure 15 shows the amount of consumption of WPC for different applications in Europe in 2012. WPC is mostly used for decking market with 67% followed by auto interior parts with 23%. 260,000 tons of WPC was produced in the year 2012 in Europe alone. (Kunststoffe 2013).

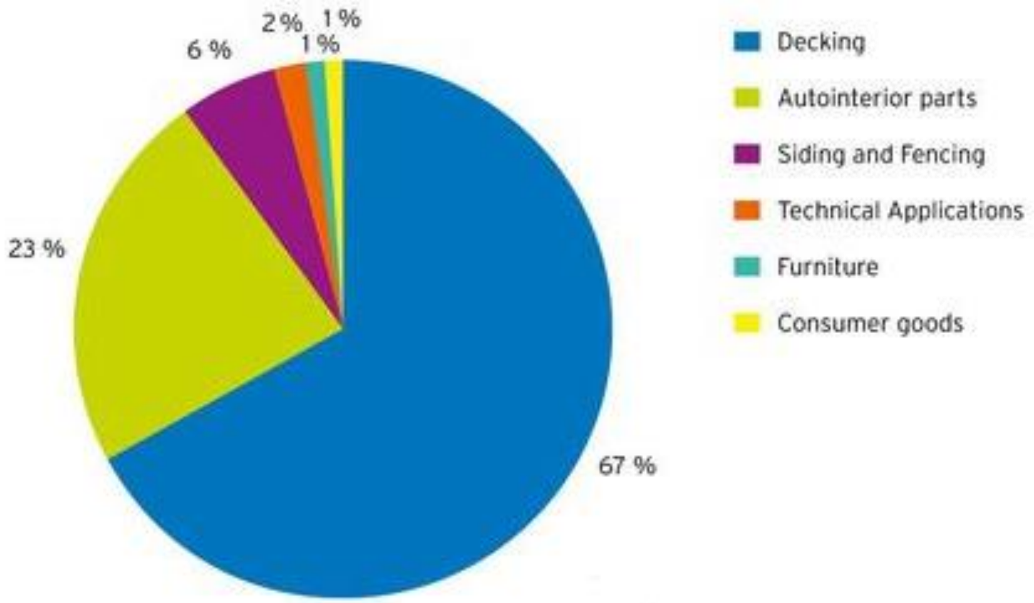

Figure 15. Applications of WPC in Europe in 2012 (Kunststoffe 2013).

1.4 Joining of Plastics and Wood Plastic Composites

The basic plastic joining techniques are shown in Figure 16. Mechanical joining is done by using of fasteners, screws. Adhesive bonding is done by using adherents between the joining parts. It is known as the best way to join dissimilar materials. Comparing to mechanical joining and welding, adhesive bonding has numerous positive aspects like: joining of dissimilar materials, increasing fatigue resistance, perfect surface finishing, low stress concentration, easiness in repairing etc. And, in welding process, joining is done by heating the surface of the polymer which enables the intermolecular diffusion giving the joint strength (Grewell, Benatar and Park 2003, p 2.)

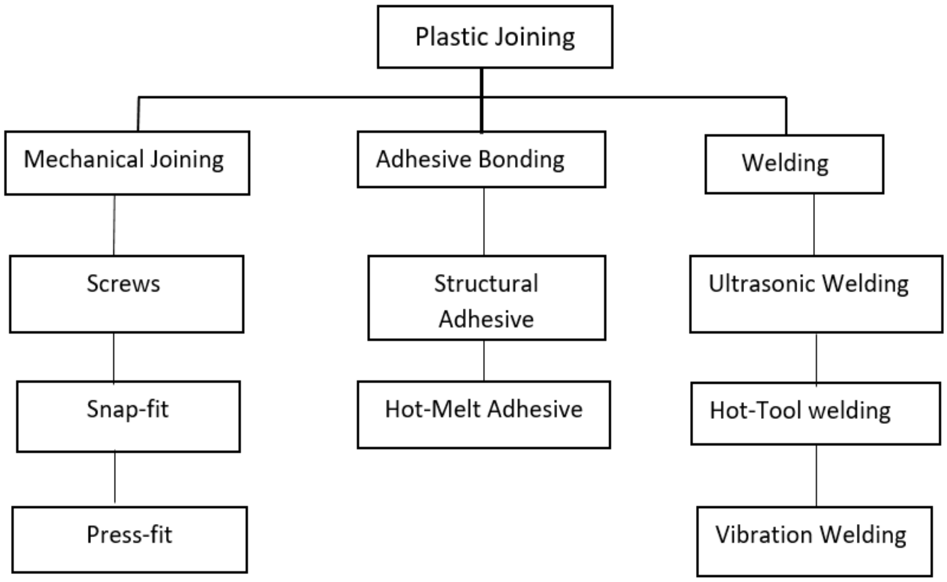

Figure 16. Plastic and composites joining processes (Grewell, Benatar and Park 2003, p. 2).

In this research work, we are solely talking about the welding of WPCs with plastics by hot gas. Although welding plastics is a growing trend in many industries, it has some limitation depending upon the plastic grades and the joint design. It should be known that only the thermoplastics can be welded.

1.5 Classification of Welding Processes

Welding processes are mainly classified based on the heating mechanism to the welding joints and they are categorized into two main classes: internal heating and external heating as illustrated in Figure 17.

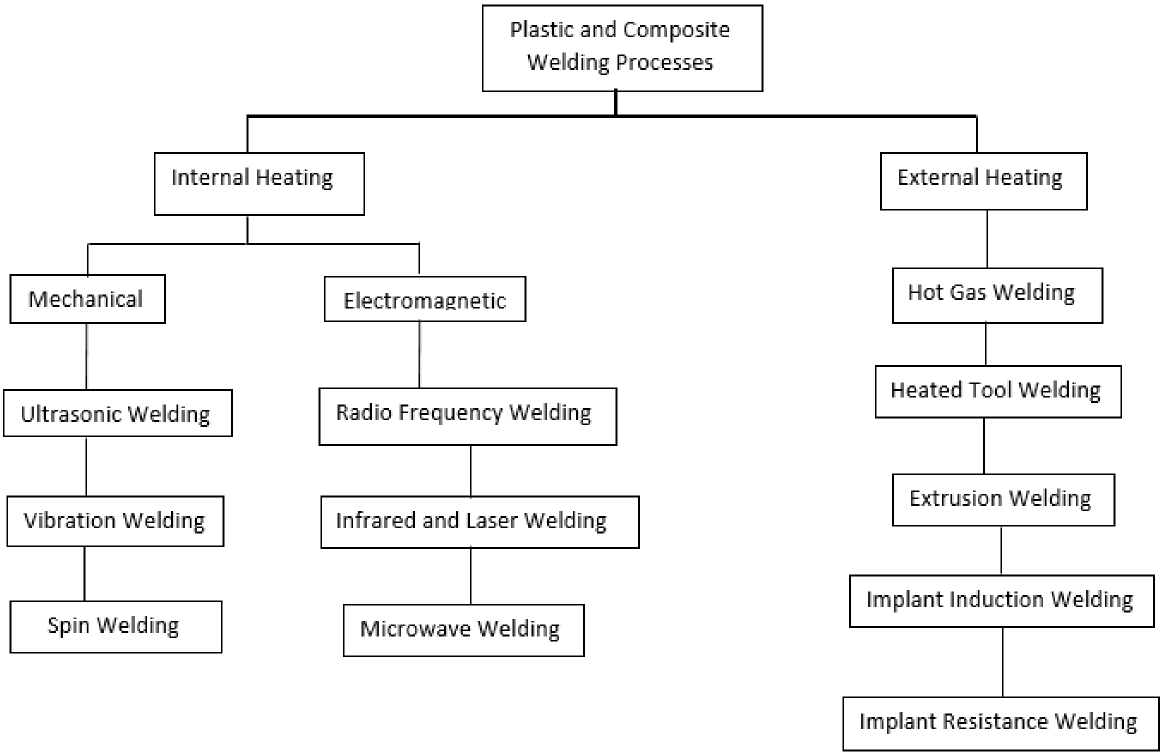

Figure 17. Plastic and composite welding processes classification (Grewell, Benatar and Park 2003, p. 7).

Plastic welding is all about the melting and fusing thermoplastics at the joining interface. Because of intermolecular diffusion around the joining interfaces, the bond occurs. There are five important steps in plastic composites welding, they are surface preparation/cleaning, pre-heating and heating, pressing, intermolecular fusion and cooling (Grewell, Benatar and Park 2003, p. 11).

Surface preparation or cleaning is the first step in plastic composites welding. Contaminations on the joining surfaces hinder the joining strength. Basically, solvent is used to clean or degrease the welding surfaces (Grewell, Benatar and Park 2003, p. 12).

Second step is heating the surface near the welding interface. It is the most important step on plastic composites welding because welding cannot be achievable without softening or melting the joining interface on both parts. It is necessary to exceed the glass transition temperature in case of heating amorphous polymers to ensure the proper diffusion. In case of semi-crystalline polymers, it is necessary to exceed the melting temperature to form a melting layer (Grewell, Benatar and Park 2003, p. 14).

After heating is done, pressing the heated zone is required to form intimate contact between the welding parts. This step is done in two steps. In first step, deforming a welded surface and intimate contact of parts is achieved. In second step, squeezing of melted layer is done and contaminations are displaced (Grewell, Benatar and Park 2003, p. 18).

Intermolecular diffusion step is needed to form a perfect weld. The phenomenon of intermolecular diffusion or chain entanglement of thermoplastic polymer interface can be called as autohesion. Autohesion process can be done in five steps, they are:

a) Surface rearrangement
b) Surface approach
c) Wetting
d) Diffusion
e) Randomization. (Grewell, Benatar and Park 2003, p. 23).

The final step on plastic composites welding is cooling and re-solidification of melted polymers at the welded zone. In this phase, semi-crystalline structure is fully crystallized to obtain the final micro-structure. During cooling, distortion and residual stress occur. For instance, in hot gas welding, bending distortion normally occurs during cooling of the welded materials (Grewell, Benatar and Park 2003, p. 26).

1.6 External Heating Technique

External heating technique depends on conduction to heat the welding surface. This process includes: hot gas welding method, hot plate welding, extrusion welding, implant induction welding and implant resistance welding (Grewell, Benatar and Park 2003, p. 7).

1.6.1 Hot Gas Welding

Hot gas welding is one of the examples of external heating techniques. It is the most popular, cheap, versatile means for joining the thermoplastics (Fasce et al., 2007). This process was based upon the traditional oxy-acetylene gas welding of metals where the heated gas was used as a heating source. In this process, flow of hot gas is used to soften the filler rod and the welding joints to reach the melting temperature of the joining materials (Amanico-Filho and Dos Santos 2009). Basically, filler rod which is made by the same composition as of welding materials is used. Mainly round cross-sectional filler rod is used but oval, triangular and rectangular cross sectioned filler rods are also available. (Haque and Siddiqui 2016). Hot gas which may be air, nitrogen, argon is supplied through the nozzle. The major applications are: fitting plastic basin, car bumpers, plastic parts, chemical containers etc. (Marczis and Czigány 2006). Some general manual hot gas welding mechanism with filler rod is shown in Figure 18.

Figure 18. Manual hot gas welding with filler rod (Reddy 2015.)

In hot gas welding process, gas is heated either by electrically or by flame and for the safety purpose, operating voltage is used as maximum as 36 volts. Welding torch has no open flames thus making suitable to use in room with inflammable materials.

In three different ways, hot gas welding process can be performed: manual hot gas welding as shown in Figure 18, speed welding mode and automated mode. As name suggests, in manual welding process, operation is performed manually, or welding rod is moved or pushed by the operator. In speed welding process, welding speed is higher because of using pressure shoe or tongue in the tip. In automated mode, welding process is done automatically thus special equipment or arrangement is done for specific applications. Hot gas welding process is applicable for thermoplastic materials like: polypropylene, polyethylene, polyvinyl chloride, polycarbonate and polyamide. (Amanico-Filho and Dos Santos 2009). The welding temperatures of hot gas stream varies for different plastic types. They can be from 175°C to 600°C (Fasce et al., 2007). Some welding gas temperatures for different plastic classes are illustrated in Table 2 and hot gas welding parameters are shown in Table 3.

Table 2. Welding gas stream temperatures for different plastic types (Fasce et al. 2007).

Plastic types	Welding temperature
Polypropylene	(300 – 320) °C
ABS	350°C
Acrylic	350°C
Hypalon	600°C
Polyethylene	(250-300) °C
Polyisobutylene	600°C
PVC	(220-300) °C

Table 3. Hot gas welding parameters (Grewell, Benatar and Park 2003, p. 76)

Parameters	Description.
Temperature	Hot gas temperature
Gas	Composition of hot gas (air, nitrogen, oxygen, carbon dioxide or hydrogen)
Angle	Angle between welded joint and rod Angle between gas nozzle and welded joint
Travel speed	Rate at which the welding is done or the rate at which the weld melt is deposited.
Weld force	Force applied to the welding filler rod
Filler rod	Composition of filler rod that use in welding joint
Gap distance	Distance between gas nozzle and welding joint
Weld joint	Joint design like: butt joint or double strap fillet joint
Pressure of hot gas	Pressure of hot gas flowing out of the nozzle
shoe	Design/size of welding nozzle

It is always a challenging task to get hundred percent perfect weld result. Minor carelessness or negligence could lead to some defects on the weld joints. Welding defects can occur on the surface of weld joint or could occur inside the weld metal. Thus, proper guidelines should always be adopted. Some common hot gas welding defects are listed in Table 4.

Table 4. Hot gas welding defects/imperfections (Grewell, Benatar and Park 2003, p. 82)

Hot gas welding defects	Description
Cracks	They can occur in welded joints, base material or in heat affected zone (HAZ). Cracks can be with or without branching, occur length wise of crosswise to the weld area.
Welding flash notches	Mainly caused by defects on die or by poor welding rod guidance
Root not weld through	Formation of incomplete weld filling at root. It can be caused by making angle too small, root gap too small, using too thick filler rod, or by applying too small welding force
Weld root too high	The main reasons of forming this defect can be because of applying root gap too big

Specific or very limited joint designs are adopted for hot gas welding procedure. Some commonly used joint designs are: Single butt joint or V joint, double butt joint, T joint, lap joint and corner joint. Figure 19 shows the common example of single V joint.

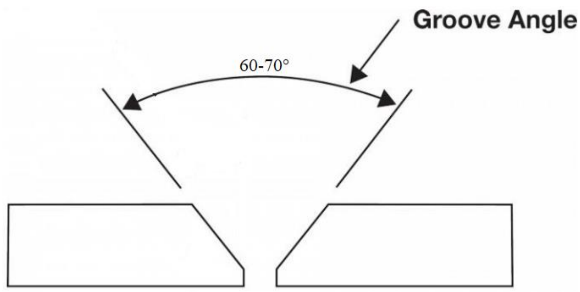

Figure 19. Single V joint (Raut 2016).

In double V joint design. Grooves are made on both sides of the welded joint whereas penetration can be full or partial as shown in Figure 20.

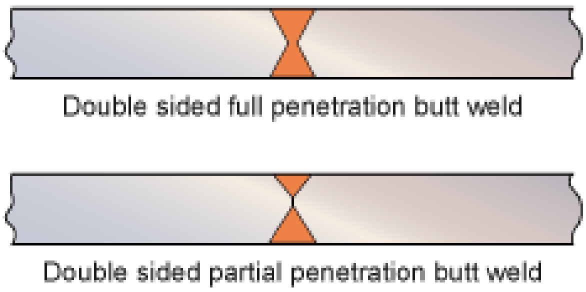

Figure 20. Double V joint. (Twi-global 2018).

As shown in Figure 21, a square T joint requires fillet weld on both sides of the joint. This type of joint is mainly applicable for light or thick welded materials.

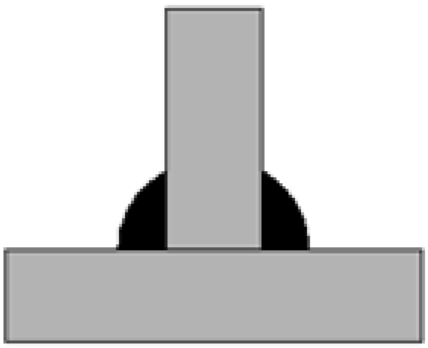

Figure 21. Square T joint (The Welding Master 2017).

The other way of welding T joint is by Single bevel T joint. This type of joint is much stronger and can resist much load than square T joint due to better distribution of stresses. Typical form of single bevel T joint is shown in Figure 22.

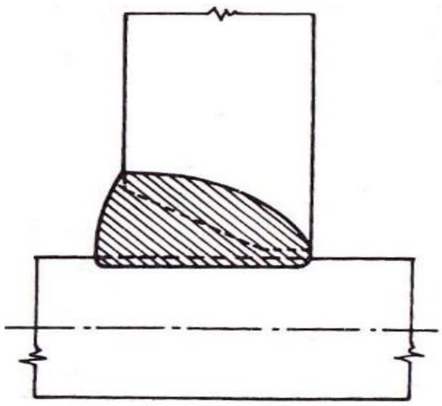

Figure 22. Single Bevel T joint (Ecourseonline 2013).

Double bevel T joint is another commonly used T joint design and mostly applied when the heavy loads are in action. Common double bevel T joint is shown in Figure 23.

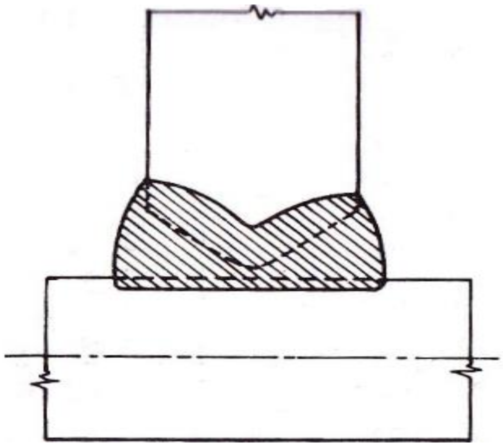

Figure 23. Double bevel T joint. (Ecourseonline 2013).

As name suggested, corner welding is done on the corners of the welding materials. There are different forms of corner welding designs. Corner weld design is shown in Figure in 24.

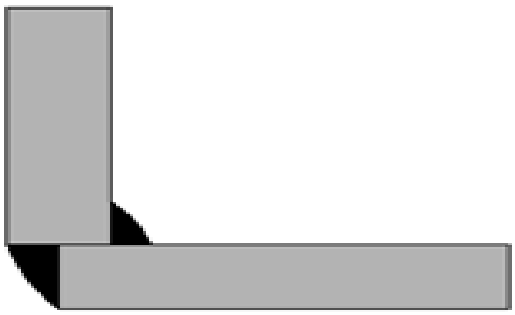

Figure 24. Common corner joints (Weld Guru 2018).

Lap fillet joint is done when one piece is welded in an overlapping format on the other piece. Fillet weld can be done on both side or on one side only. Fillet lap joint side is shown in Figure 25.

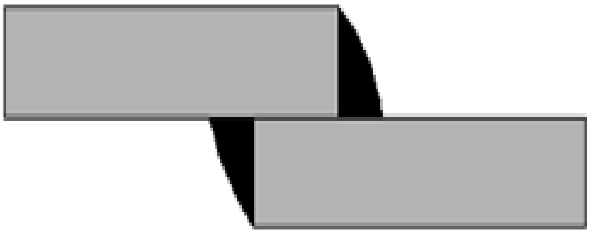

Figure 25. Lap fillet joints (The Welding Master 2017).

1.6.2 Hot Plate Welding

Heated tool welding or commonly known as hot plat welding is mostly used welding techniques for thermoplastics due to its reliability, simple method and good quality weld. In this method, heated tool brings in contact or against with the joining materials so that the surface of the joining workpieces gets molten. After the desired molten surface is gained, heated tool is retracted and the joining surface is compressed or squeezed by the constant pressure in order to form a proper fusion and thus weld is formed. The major applications of this type of welding techniques are: in automotive, civil engineering, pipeline industries, construction. (Amancio-Filho and dos Santos 2009, p. 1465). Heated tool welding technique is mostly suitable welding process for injection molded, blow molded and extruded hollow parts. Common hot plate welding machine is shown in Figure 26.

Figure 26. Heated tool welding machine (Directindustry 2018).

To insure a good weld quality, the temperature of heated tool should be in the range of melting temperature of polymers. Some major welding parameters are: squeezing pressure, heating time, temperature of the heated tool, parts preparation, cooling time, welding time. Some major benefits of hot plate welding are listed below:

- No need to filler rod
- High production rates
- Easy to assemble
- Many different types of materials can be welded
- Low emissions. (Amanico-Filho and Dos Santos 2009, p. 1464).

In contrast, some drawbacks of heated tool welding are listed below:

- High energy consumption
- Presence of residual stress
- Expensive equipment
- Start-up is slow, normally (15-30 minutes) (Amanico-Filho and Dos Santos 2009, p. 1464).

Unlike hot gas welding, there are many points to be considered while using hot plate welding technique. Some of the necessary design requirements are listed below:

- Welding parts should be perfectly fixed on the fixture thus should withstand the applied pressure
- Joining materials should have identical joining shapes and sizes surfaces

- To avoid the misalignments, clamping fixtures should be in contact near to the joining surface
- Welding parts' surfaces should be as flat as possible
- To avoid thermal distortion of other parts than joining area it is necessary to maintain a good distance of joining surfaces to the non-contact heating tool. (Grewell, Benatar and Park 2003, p. 45).

1.6.3 Extrusion Welding

Extrusion welding is done on the principle of hot gas welding mechanism. In this process, molten polymer which is in the form of rod or as filler is extruded on the joining surface. Hot gas is used to heat up the joining line to increase the bonding strength of the joint (Amanico-Filho and Dos Santos 2009, p. 1466). Instead of hot gas, sometimes radiant heat from halogen lamps can also be used. Simple illustration of working principle of extrusion welding is shown in Figure 27.

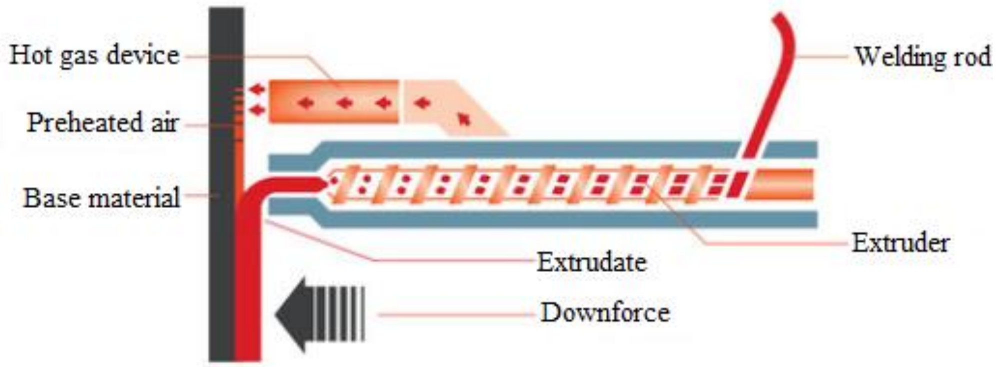

Figure 27. Working principle of extrusion welding (DEMS 2016).

In this method, welding rod is fed to the extruder, which melts the rod (polymer) and finally gets deposited on the welding joint which is finally pressed by the shoe-tool. Workpiece with thickness of about 30mm maximum is suitable for this welding procedure. The main welding parameters include: good surface preparation, position of extruder, temperature of hot gas and extrusion, welding speed, pressure and design of shoe-tool surface. The main advantage of extrusion welding is it has very short period of welding cycles than any other welding processes (Amanico-Filho and Dos Santos 2009, p. 1466).

This welding process is mostly done for PP and HDPE but also possible for PVC and Polyvinylidene Fluoride (PVDF) with the special equipment. The main advantage of extrusion welding process to hot gas welding process is getting continuous weld bead with single weld pass whereas multi pass should be done in hot gas welding. Moreover, it has higher weld strength than hot gas welding. Extrusion welding is mostly used in making large thermoplastic products, like: tanks or pipes' sections when producing in a large number, making landfill waste sites, roof coverings where the homogenous weld is needed with a single weld pass (Troughton 2008, p. 73).

1.6.4 Implant Induction Welding

Induction welding is an example of solid-state welding that works on heating the gasket (placed between the joining parts) by the means of induction. In other words, electromagnetic field of about 2-30 MHz is delivered around the joint interface with the help of induction coil. Thus, it is necessary to have the conductive thermoplastic compounds. In the presence of alternating magnetic field, filler in the gasket gets heat and eventually leads to the melting of polymer in gasket and on the surface of the two joining surfaces. After the sufficient amount of heating, electromagnetic field is turned off and allowing the cool and pressure is applied to join the melted surface. The gasket remains on the welded part permanently. The main advantages of induction welding include: high production rates, welding dissimilar materials is possible, strong joints, free of distortion, vapor-proof, high pressure joints. On the other hand, some disadvantages of induction welding are: filler material required, expensive equipment, complex assembly operations, greater chance of heating other metallic materials due to electromagnetic field etc. The major applications of induction welding are: automotive parts, household appliances, sealing plastic catted metal foil tops. (Amanico-Filho and Dos Santos 2009, p. 1467). Simple illustration on induction welding process is shown in Figure 28.

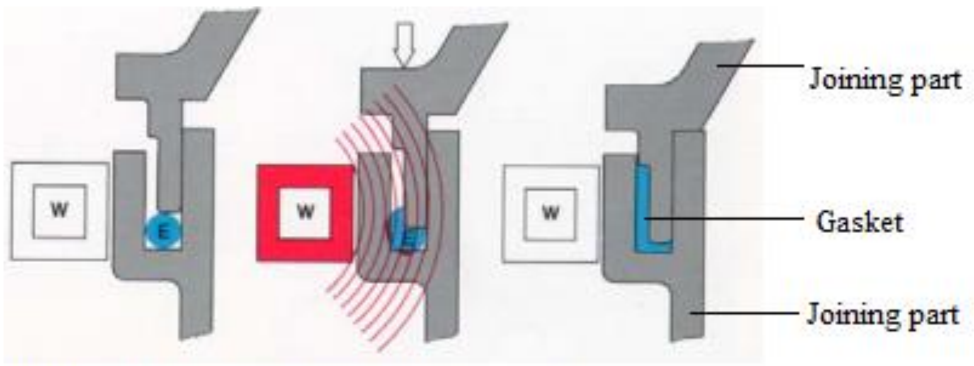

Figure 28. Implant induction welding phases (Kagan and Nichols 2004, p. 4).

The major parameters for induction welding are listed below:

- Magnetic permeability of susceptor implant
- Flexibility of joint design
- Compatibilty of polymer applied in magnetic susceptor implant with the materials to be joined
- Optimization of necessary welding parameters for ultimate joint performance.

1.6.5 Implant Resistance Welding

Implant resistance welding is one of the popular welding processes for thermoplastics in which an electrically resistive implant is used between the two joining surfaces in order to generate heat. The generated heat melts the joining surface and bonding occurs. This welding technique requires very simple welding tools and needs very less surface treatment (Stavrov and Bersee 2005, p. 40). General working technique of implant resistance welding is depicted in Figure 29.

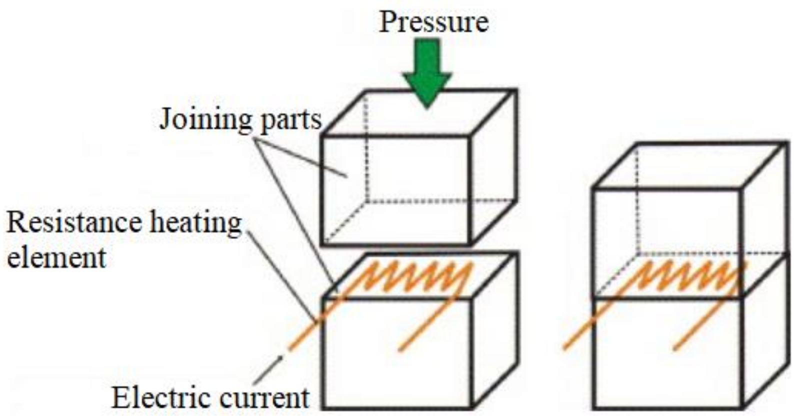

Figure 29. Implant resistance welding working principle (Stavrov and Bersee 2005, p. 40).

When the current passes through heating element, the temperature of implant rises above the glass transition or the melting temperature of the used thermoplastic materials, thermoplastic matrix of the workpieces start to melt. After the sufficient melting is achieved, supply current is stopped and adequate pressure is applied for the sufficient joint forming (Stavrov and Bersee 2005, p. 40). Some positive aspects of implant resistance welding are listed below:

- Cheap equipment
- Simple setup
- Easy to weld almost any size of parts
- Easy to disassemble the welded parts.

In contrast to it, this welding technique also has some negative aspects like:

- Implants remain between the joining parts
- Long welding cycle
- Skilled manpower is needed
- Because of implants, it’s unsuitable for recycling (Grewell, Benatar and Park 2003, p. 123).

1.7 Internal Heating Technique

Internal heating technique can be done by two mechanisms. They are: internal mechanical heating technique and internal electromagnetic heating technique (Grewell, Benatar and Park 2003, p. 7).

1.8 Internal Mechanical Heating Technique

Internal mechanical heating technique is based on the process of conversing mechanical energy into heat through the friction. This process includes the welding processes like: ultrasonic welding, vibration welding and spin welding (Grewell, Benatar and Park 2003, p. 7).

1.8.1 Ultrasonic Welding

In today’s time, there are various products or items made by plastics not only for daily purposes but in ships, toys, automobiles, aviation and also in many electronic companies. Depending upon their purposes and usability, their shapes can be complexed, and plastic parts are impossible to be formed by injection molding thus, they need to be joined using adhesive or welding. One disadvantage of using adhesive is its lower efficiency plus toxicity in various adhesives (Huang 2012, p. 871).

Some general ultrasonic welding principle is shown in Figure 30 where the joining parts are clamped between sonotrode tip and anvil. Transducer helps in converting the provided electrical frequency into ultrasonic high frequency energy. Ultrasonic welding uses that high frequency of about 10-70 kHz along with low amplitude of around 10-50 µm vibration to weld the parts. Vibration creates cyclical deformation mostly on the joining surfaces. That cyclical energy finally gets converted into heat which is able to melt the surface of thermoplastics through intermolecular friction thus forming fusion-bond of the joining parts. (Grewell, Benatar and Park 2003, p. 141).

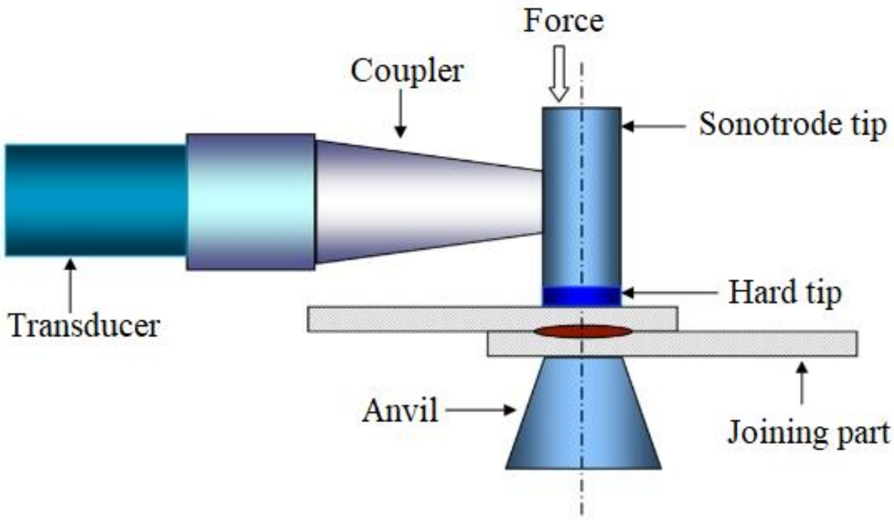

Figure 30. Working principle of ultrasonic welding (Typesofwelding 2018).

1.8.2 Vibration Welding

Vibration welding is the most common joining technique for thermoplastics in industrial applications. The main mechanism of this process involves rubbing together the interfaces or surfaces of joining materials until they get molten and bond is created after they are solidified (Grewell, Benatar and Park 2003, p. 189). This process is well known for fast operation, reliable joint and well suited for wide range of materials and applications (Grewell and Benatar 2003, p. 1410). Main applications of vibration welding include: lighting assemblies, battery casings, fuel tanks, sealing hollow regions etc. (Patham and Foss 2011, p. 3). Simple illustration of working principle of linear vibration welding is shown in Figure 31. There are mainly four vibration welding processes:

- Linear vibration welding
- Orbital vibration welding
- Angular vibration welding
- Spin/rotational vibration welding (Grewell, Benatar and Park 2003, p. 189).

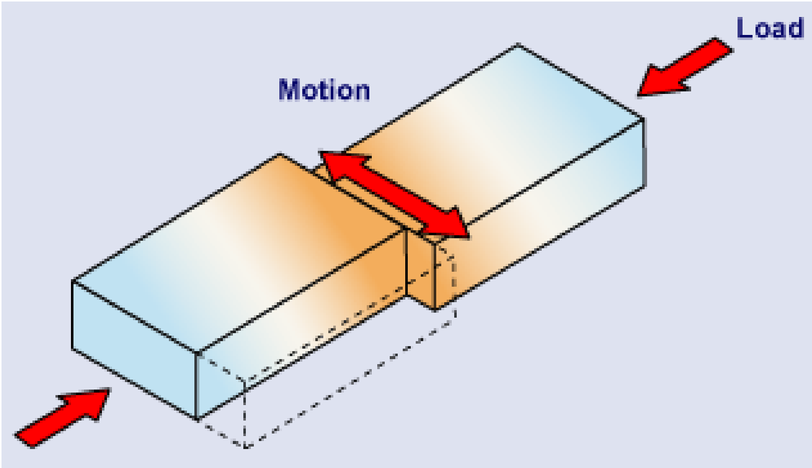

Figure 31. Principle of linear vibration welding (Kallee 2000).

The main advantages of vibration welding include:

- Simple processing without complex accessories like: ultrasonic horn
- No surface preparation needed
- Possible to join large parts, irregular shaped joining parts, curved surface (Patham and Foss 2011, p. 3).

1.8.3 Spin Welding

Spin welding is used for joining thermoplastics parts in which joining surfaces are rotationally rubbed with pressure about an axis normal to the welding surface. One part is rotated to another stationary part. Rubbing on part eventually generates friction leading to melt the joining surface and after rotational motion is withdrawn, molten surface is allowed to cool down and with pressure it is forced to join as it solidifies (Stokes 1988, p. 2772). General working principle of spin welding is shown in Figure 32.

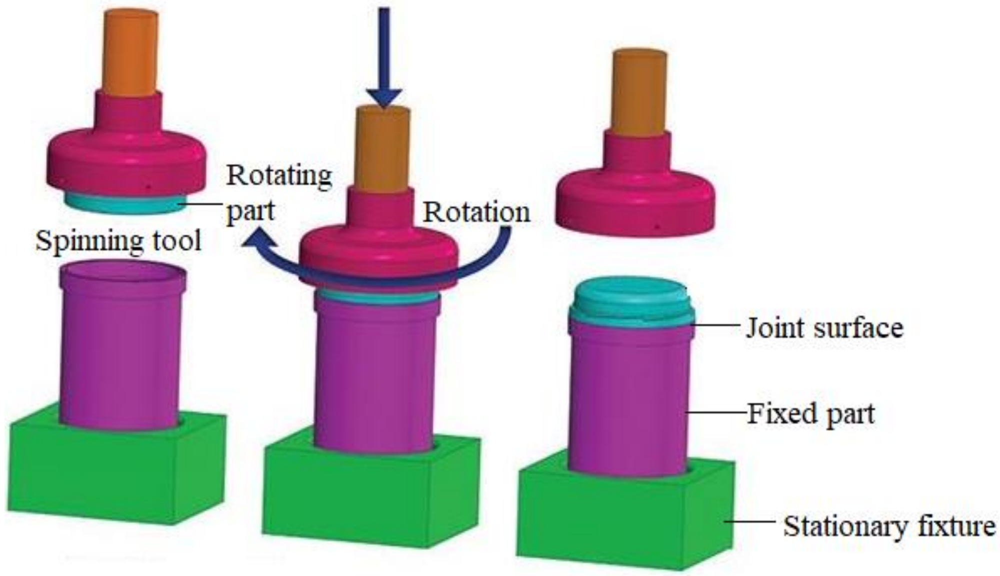

Figure 32. Working principle of spin welding (Frantz 2013).

The main advantages of spin welding include: short cycle time, simple welding equipment, surface preparation is not required (Stokes 1988, p. 2772). Some major applications of spin welding are: truck lights, welding thermal drinking cups, plumbing, joining rubberized cork with acetal gear (Grewell, Benatar and Park 2003, p. 241).

1.9 Internal Electromagnetic Heating Technique

Internal electromagnetic heating technique works on the principle of conversing electromagnetic radiation into heat to melt the welding surface. This methods include: radio frequency welding, infrared and laser welding and microwave welding (Grewell, Benatar and Park 2003, p. 7).

1.9.1 Radio Frequency Welding

Radio frequency welding is commonly called as dielectric welding and only relies on polar polymers. Heat is generated on the joining surface by dielectric hysteresis losses of polymers/thermoplastics. On the presence of high alternating electric field, the dipoles of polar thermoplastics get reoriented according to field polarity which results in generating heat that eventually melts the surface of joining parts. Finally, pressure is applied to join the melted surface (Amanico-Filho and Dos Santos 2009, p. 1468). General working principle of radio frequency welding is shown in Figure 33.

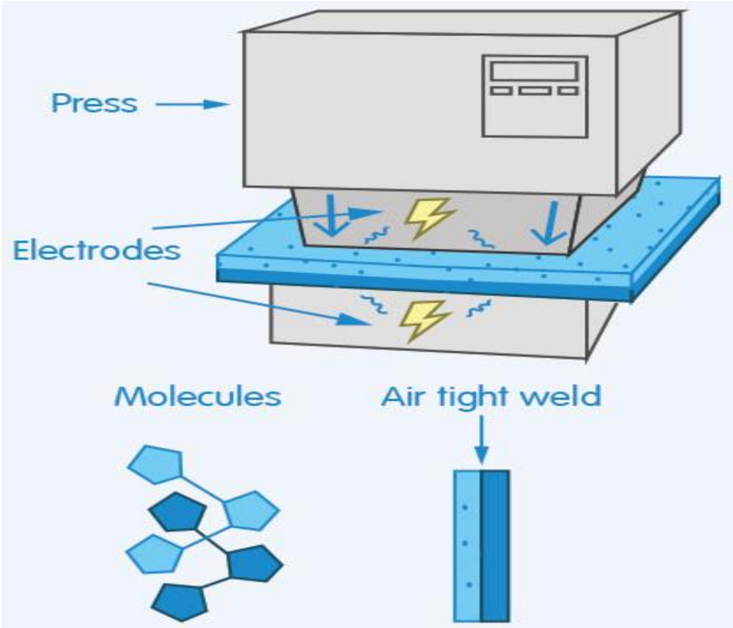

Figure 33. Working principle of radio frequency welding (Fxi 2018).

Some thermoplastics that can be welded by radio frequency welding process are: PVC, Chlorinated polyvinyl chloride (CPVC), polyurethane, nylons, cellulose acetate, PET PETG. (Grewell, Benatar and Park 2003, p. 249). The main application of this welding process is for welding thin sheets or films, medical blood or fluid bags, ring binders and stationary wallets (Amanico-Filho and Dos Santos 2009, p. 1468).

1.9.2 Infrared and Laser Welding

Infrared and laser welding is nowadays mostly popular in industrial applications as the price for laser units are getting cheaper and offering higher power output (Potente, Karger and Fiegler 2002, p. 734). In the present world, various kinds of thermoplastics are being welded with sources of laser. Although this technique is well known for higher accuracy and used in mass production, various researches are focusing on laser polymer welding optimization (Mingareev et al. 2012, p. 2095).

There are mainly three modes of infrared and laser welding, they are:

- Through transmission IR welding
- Surface heating
- IR/laser staking.

In through transmission IR welding, laser beam is passed to one of the joining parts having IR transparent and other part absorbs the supplied radiation. This technique is mostly suitable for joining automotive taillights.

Surface heating welding process is somehow similar to hot plate welding method where the laser beam is exposed to the joining parts for a certain period of time. After the joining parts are fully melted, laser beam is withdrawn and force is applied to the joining parts and allowed to solidify (Grewell, Benatar and Park 2003, p. 271).

Laser staking is simply a combination of riveting and laser plastic welding process (Humbe et al. 2014, p. 196). This process is mostly used when the materials cannot be welded or it is used to joint metals to thermoplastics. In this welding technique, thermoplastic stud is softened and deformed by the laser radiation into a cavity which captures the molten plastic to form the desired button geometry. It is always necessary to make the upper surface of the cavity to be fabricated with transparent material to ensure the direct projection of laser beam to the stud. (Grewell, Benatar and Park 2003, p. 271).

1.9.3 Microwave Welding

Microwave joining mechanism for thermoplastics is rapidly growing trend in manufacturing processes. In this welding process, electromagnetic energy is absorbed by the joining materials that results in volumetric heating instead of progressive heating unlike of conventional welding. The provided microwave generates heat by different mechanisms like: magnetic permittivity, eddy currents or loss tangent mechanism or the combination of all. That results in rapid heating, uniform distribution of heat and highly energy efficient. The microwave frequencies range from 300 MHz to 300 GHz. The main advantages of microwave welding process include: fast joining time, reliable joint strength. (Roychoudhury, Sharma and Singh 2012, p. 87).

Microwave welding to the thermoplastics is done by placing an absorbing material like metal or any other conducting polymer between two joining parts and exposing whole assembly parts to the microwave energy. Thermoplastics are transparent to microwave radiation but absorbing material or gasket acts as a consumable thus heat is generated in there which in result melts the thermoplastics and is allowed to solidify to form the bond. (Grewell, Benatar and Park 2003, p. 313). General microwave welding process is shown in Figure 34. The main applications of microwave welding include: automotive parts such as, bumpers, body panels, dashboards, load floors etc. (Twi 1996)

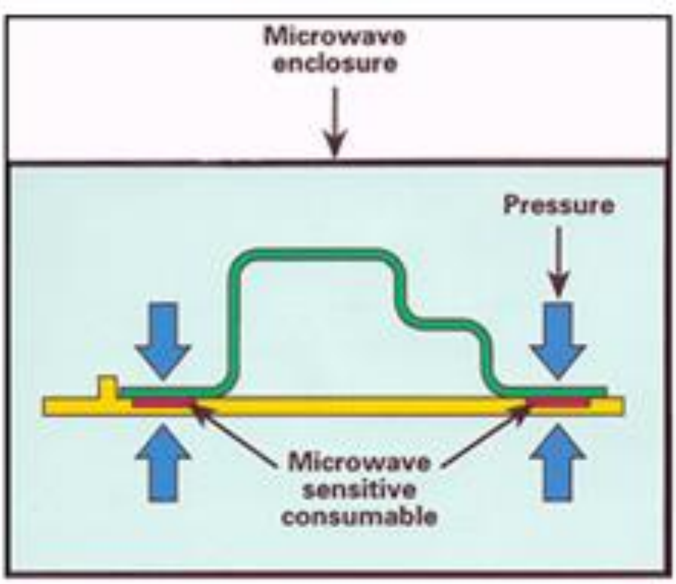

Figure 34. Microwave welding process (Twi 1996).

1.10 Objective

The main objective of this study is to identify the proper filler wire that provides good joint strength to the welded WPCs. Different filler rods will be used, and tensile strength and tensile modulus tests will be performed to identify the weld joint strength and compare with the non-welded WPCs' samples. Furthermore, how the plastic content on WPC and filler wire will effect on welding properties also be analyzed. Finally, Scanning Electron Microscopy (SEM) test will be done to study the microscopic structures.

1.11 Research Problem and Question

Nowadays, demand and production of WPC is increasing because of it various properties, like: waterproof, durability, UV-resistant, easy to install, low-maintenance cost. It is possible to make various shapes and sizes of WPC's structures or products but what if the WPC structure is broken or damaged. What if the structure needs to have joints that are more complex? Then welding WPC might be good option for such scenario.

This research is about the welded joint strength of WPC. So, the suitable research questions could be: what type of filler wire is suitable for certain type of WPC, how the amount of plastic percentage in WPC's base materials and filler rods effect on its weldability and joint strength, is welded WPC good to use, are they reliable and durable. Therefore, the research will have some experimental test to collect the necessary data to evaluate and analyze the nature of welded joint of WPCs' samples. The outcome of this research will give some idea to know about the welded WPC, it's strength, usability and possibilities.

2 MATERIALS AND METHODS

Mainly two classes of composites were used in this research. One sample was named as HDPE_60 (contains 60% PE) and other as HDPE_70 (contains 70% PE). Both samples were HDPE but slightly differed in plastic contents and mesh spruce percent. Moreover, different filler wires were used to join the base materials. They were: pure PP, pure PE, filament extruded PP (10% cellulose), filament extruded PE (10% cellulose) and the filler wire same as the base materials. 15 samples were tested for each test pieces using 5 different filler wires. Thus, total of 180 tests were done. More specifications of baser materials and filler wires are shown in Table 5 and 6 respectively.

Table 5. Specifications of base materials

Base Materials	Contents
HDPE_60	60% HDPE, 34% mesh spruce (20 size), 3% coupling agent and 3% lubricant
HDPE_70	70% HDPE, 24% mesh spruce (20 size), 3% coupling agent and 3% lubricant

Table 6. Specifications of filler wires

Filler wires	Contents
Commerical PP	Polypropylene
Commercial PE	Polyethylene
Filament extruded PP	90% PP and 10% cellulose
Filament extruded PE	90% PE and 10% cellulose
Composites	Same compositions as HDPE_60 and HDPE_70

2.1 Mechanical properties

For tensile strength, the standard dimensions of the sample should have used but it is obvious for this test part that the inner width or gauze width (10 mm) is too small for the welded region and also the welded bond would get distorted while cutting the samples. Thus, to avoid the distortion or weakening of welded region while cutting, our samples had the uniform width of about 20 mm and thickness of about 3 mm as shown in Figure 35. The tensile strength and tensile modulus were tested according to ISO 527-2 standard test on Zwick Z020 machine. In order to compare the strength of welded joints with non-welded composites, tensile strength of non-welded HDPE_6 and HDPE_70 composites were also taken.

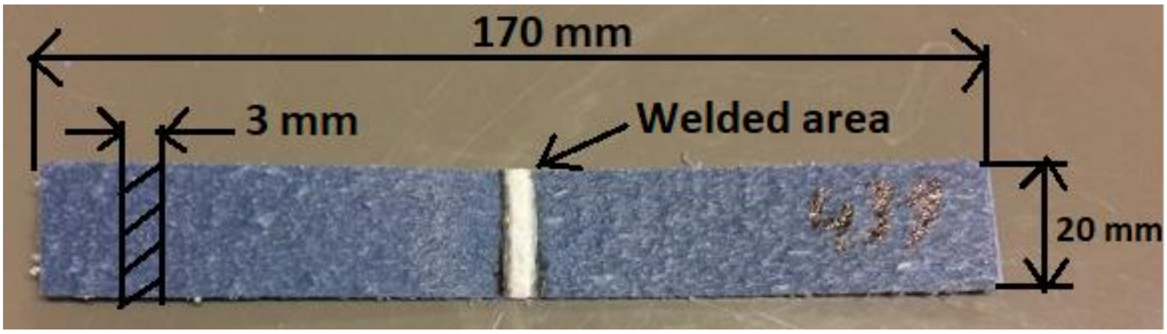

Figure 35. Dimension of the research sample.

2.2 Experimental Description

2.2.1 Experimental Procedure

Hot gas welding procedure was used for this research. As explained earlier, it used hot gas to melt the filler wire and base materials to join each other. At first, wood flour, HDPE particles and additives are mixed together with the help of Plasmec TRL 100/FV/W turbomixer or agglomeration machine. Then, HDPE_60 and HDPE_70 composite slabs of 3 mm thick were manufactured by extruded with the help of Battenfeld-Cininnati FiberEX 38 (extruded machine). The WPCs were produced with 3 mm thickness because the maximum diameter of extruder was 3 mm thick. Filament extruded PP and PE was manufactured by Filament EX2 machine. Those slabs were cut into the desired shapes with the help of cutter so that the welding can be done easily. After the cutting process was done, pieces were advanced further for welding process. Hot gas of temperature about 170 °C was used. Complete experimental procedure from beginning to end is illustrated in Figure 36.

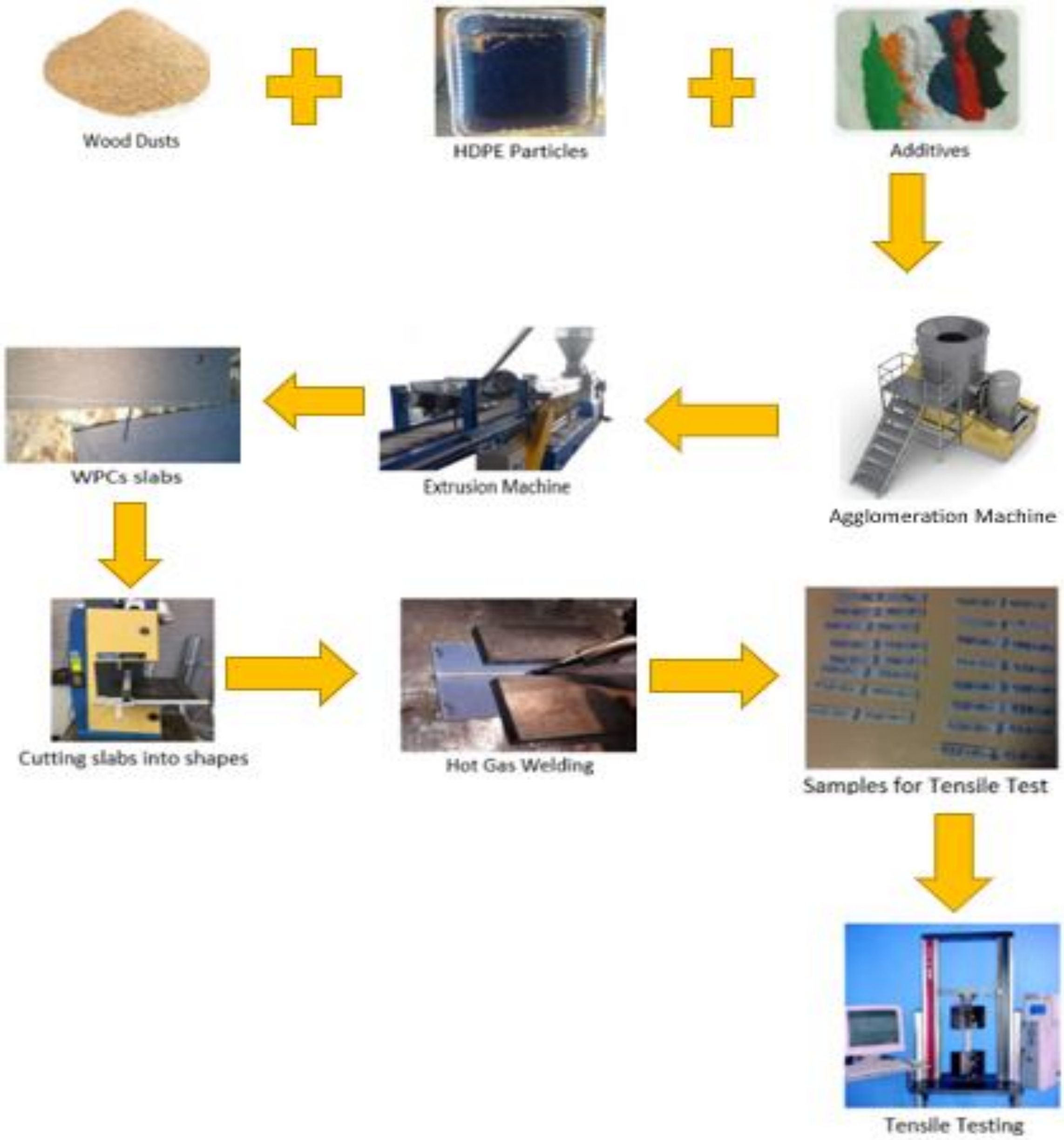

Figure 36. Schematic experimental procedure.

3 RESULTS

Wood plastic composite has been studied and done several researches in recent years due to its various benefits and the field of its applications is also increasing. It is obvious that the WPCs structures can break or tear due to unexpected environmental consequences like: overloading, sudden impact, manufacturing defects, structural design defect, poor maintenance etc. Thus, knowing the best way to repair the damaged WPCs structure is always a wise decision. On the other hand, making the large structures without any joints would nearly be impossible. Joining the damaged parts or making the joint structures could be done by the help of WPCs welding.

In this section, the results of WPCs welding with hot gas using various plastic filler wires has been analyzed and highlighted the best and worst filler wire for the given base materials. Finally, compared with the non-welded reference materials.

3.1 Experimental Results

On the viewpoint of tensile strength, the experimental results showed that different filler wires behaved differently for the given base material. Some materials showing before and after tensile testing is shown in Figure 37. It is seen that in every samples, breaking down occurred in joint area. In other words, welded joint is the weakest point in welded WPC.

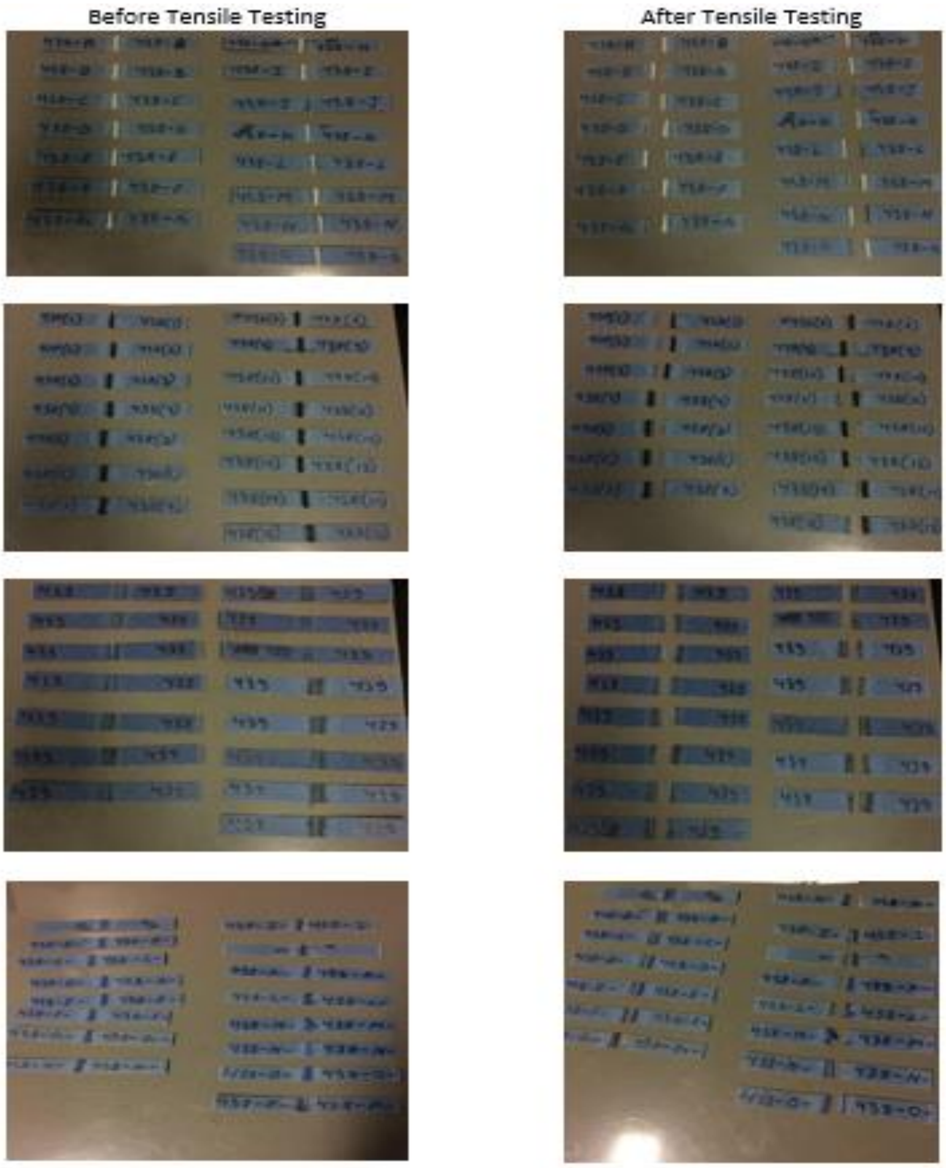

Figure 37. Different samples showing before and after tensile testing.

Table 7 and 8 illustrate the given name for each sample and their tensile strength and tensile modulus respectively.

Table 7. Given name for each sample

Samples	Given names
Reference non-welded composites containing 60% HPDE	(HDPE_60)
HDPE_60 base material with pure PP filler wire	(HDPE60_PP)
HDPE_60 base material with pure PE filler wire	(HDPE60_PE)
HDPE_60 base material with Filament extruded PP filler wire	(HDPE60_RecPP)
HDPE_60 base material with Filament extruded PE filler wire	(HDPE60_RecPE)
HDPE_60 base material with in-lab composite filler wire	(HDPE60_Comp)
Reference non-welded composites containing 70% HPDE	(HDPE_70)
HDPE_70 base material with pure PP filler wire	(HDPE70_PP)
HDPE_70 base material with pure PE filler wire	(HDPE70_PE)
HDPE_70 base material with filament extruded PP filler wire	(HDPE70_RecPP)
HDPE_70 base material with filament extruded PE filler wire	(HDPE70_RecPE)
HDPE_70 base material with in-lab composite filler wire	(HDPE70_Comp)

Table 8. samples and their tensile strength and tensile modulus with standard deviations in parantheses.

Samples	Tensile Strength (MPa)	Tensile Modulus (GPa)
(HDPE_60)	9.2274(0.7692)	1.1289(0.1832)
(HDPE60_PP)	1.6134(0.8372)	0.5565(0.3305)
(HDPE60_PE)	4.8173(1.0171)	0.7924(0.1624)
(HDPE60_RecPP)	3.5653(1.0792)	0.9306(0.2634)
(HDPE60_RecPE)	5.2463(1.5327)	1.0356(0.2140)
(HDPE60_Comp)	5.8735(1.2600)	0.8647(0.3049)
(HDPE_70)	18.0550(0.8912)	1.9167(0.1119)
(HDPE70_PP)	1.9707(0.5387)	0.4916(0.1979)
(HDPE70_PE)	5.4925(1.3286)	0.9771(0.2649)
(HDPE70_RecPP)	2.8641(0.9815)	0.6039(0.2534)
(HDPE70_RecPE)	5.6802(1.6256)	1.0351(0.2252)
(HDPE70_Comp)	8.1470(2.7362)	1.0515(0.2785)

As seen in Figure 38, sample HDPE_70 with same filler wire where the filler wire is perfectly melted on the base material giving a strong joint with tensile strength of 8.1470 MPa. The main reason of good weldability is due to higher presence of plastic content.

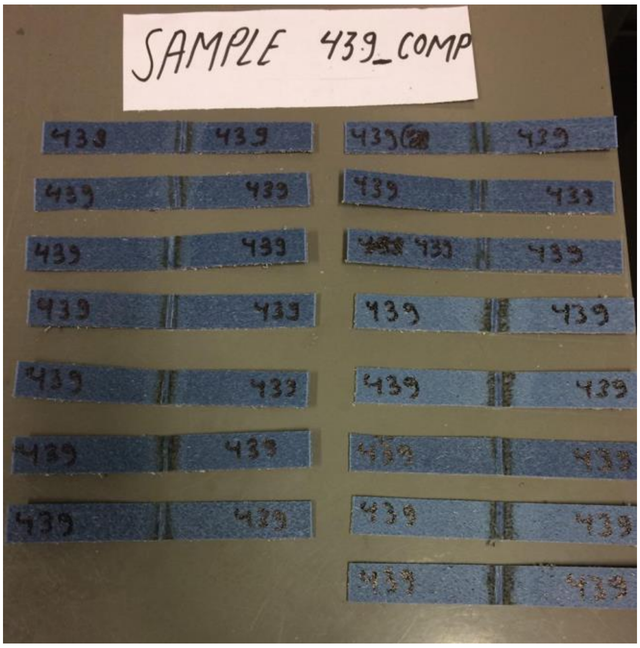

Figure 38. HDPE_70 sample with same filler wire.

As mentioned earlier, 180 teste were done for this experimental work. During the welding process, different situations have occurred, like: separation of weld joint, sometimes more and sometimes less deposition of filler wire on base materials, some filler wire melted quickly while some filler rod took a longer time to melt. Commercial PP and PE filler wires had higher melting temperature so in those situations base materials melted faster than filler wire.

During the welding procedure, it was observed that welding speed needed to be constant. Fast welding speed caused less deposition of filler wire on the welded joints whereas slow welding speed caused more deposition of filler rod on the base materials. Moreover, base materials were distorted during welding process due to hot gas and formed a noticeable gap on the joints.

4 DISCUSSION

This section is more concerned about the results of this research work. Different filler wires have different impact on the joint strength and microscopic morphology. The summary of tensile test and SEM analysis are presented in this section.

4.1 Strength properties

The tensile strength and tensile modulus of each sample is highlighted in Figure 39 and 40 respectively.

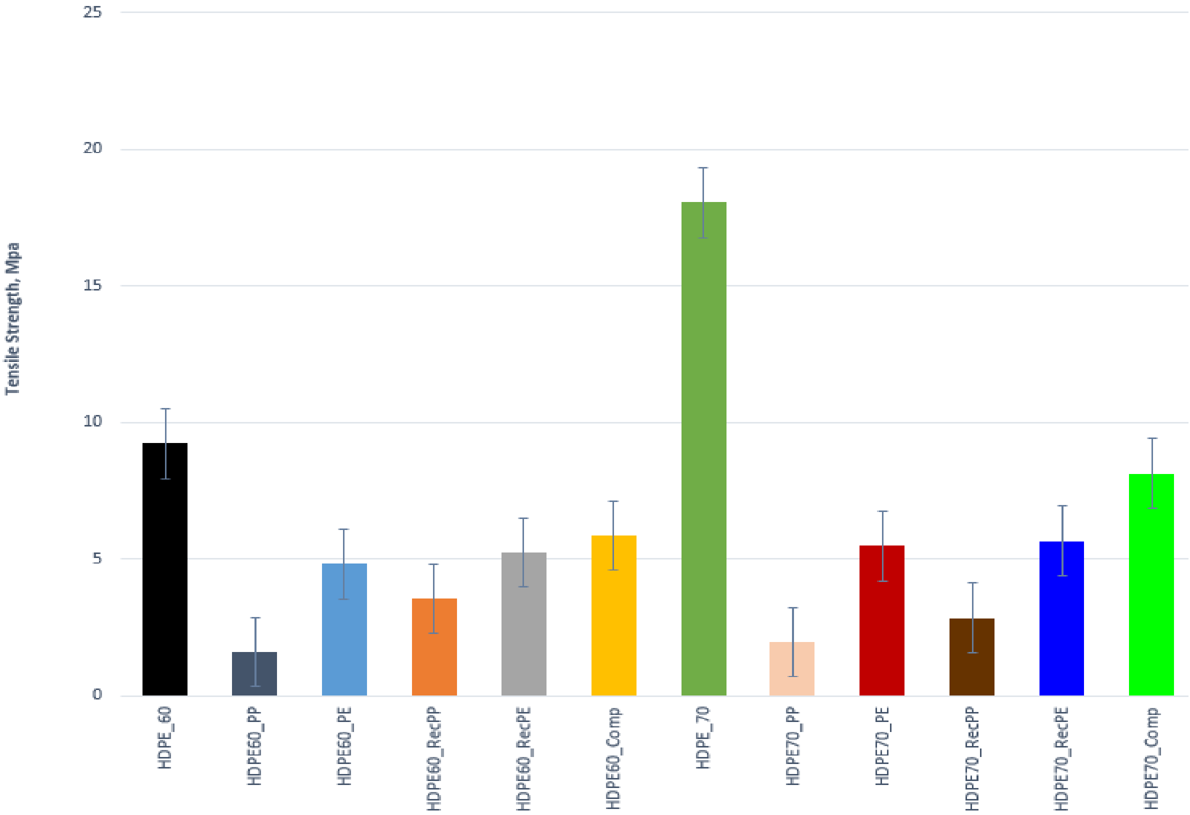

Figure 39. Tensile properties of different composite materials with different filler wires.

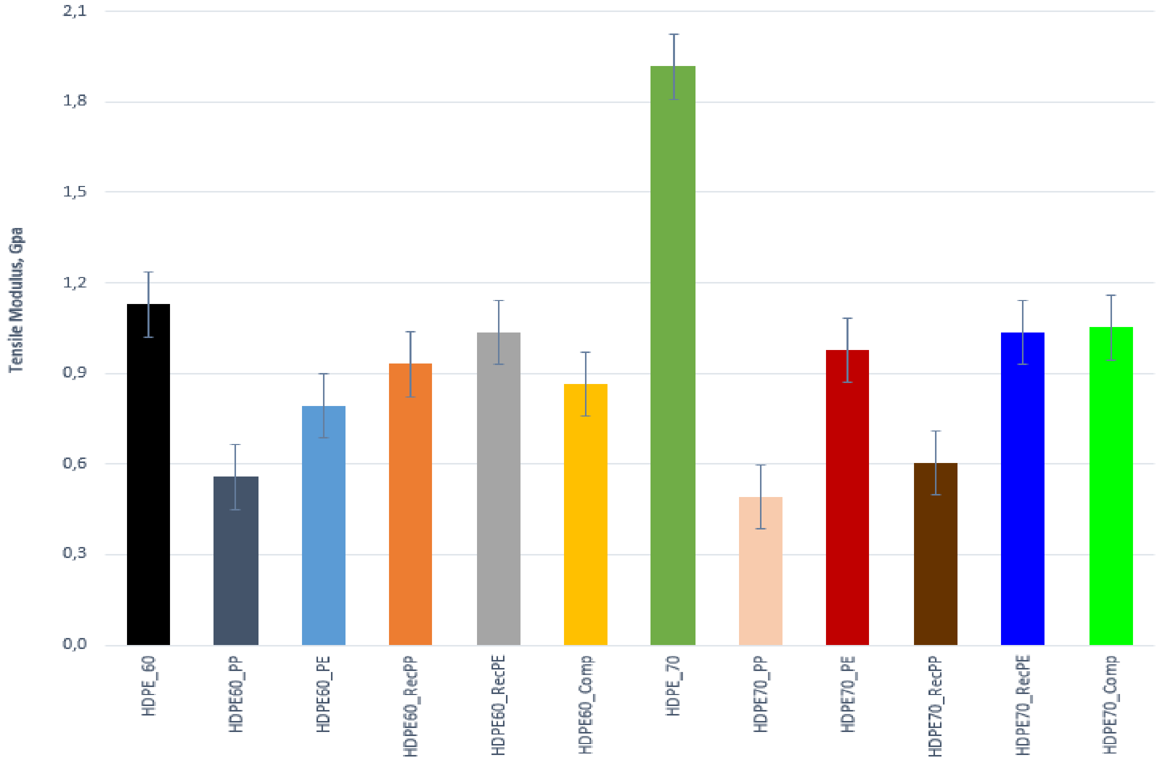

Figure 40. Tensile modulus of different composite materials with different filler wires.

Experiment showed that the nonmatching filler wire gives really a weak bond to the welded parts. For instance, pure PP filler wire showed a weakest welding joint with HDPE_60 workpiece. More information can be illustrated in Figure 39. The main reason could be the variation in melting temperature of materials. In other sense, pure PP filler wire had higher melting temperature than base materials thus base materials melted earlier than the PP filler wire causing a week bond.

The other main observation discovered by this experimental work is the sample HDPE_70 welded with composite filler wire made a good welding joint and had the tensile strength closer to the non-welded HDPE_60 reference sample. It gives the sense that filler wire needs to be the same as the base materials.

Moreover, in the tensile test, it is showed that the filament extruded PP and PE filler wires containing 10% cellulose gave the more tensile strength to the welded joints as compared to pure PP and PE. Thus, recycled PP and PE seemed to be better filler wires than commercial PP and PE.

It is obvious that non-welded structure tends to have more strength as compared to welded parts which can also be seen in table 6. Among non-welded samples, HDPE_70 workpiece has greater tensile strength of 18.0550 MPa as compared to non-welded sample HDPE_60 having 9.2274 MPa.

In case of welded samples, it is clearly seen that the welded joint will be stronger if the filler wire is used as the same composition as of base materials. In other words, filler wire needs to be the same as of joint materials. The reason behind it that when hot gas is supplied to the welding process. Both filler wire and base materials melted at the same time thus strong and uniform bonding occurred in the welded areas.

In a similar way to tensile strength values, non-welded samples showed the greatest tensile modulus. HDPE_70 non-welded sample had the highest tensile modulus with 1.9176 GPa followed by non-welded HDPE_60 non-welded sample having 1.1289 GPa. HDPE70_PP showed the lowest tensile modulus value of 0.4916 GPa which is more than three times lesser than highest tensile modulus value. In Figure 40, samples with filament extruded PE have comparatively showed good tensile modulus to other welded samples whereas commercial PP and PE showed the lowest tensile modulus values. Among the filament extruded filler wires, PE showed the better result than PP. Samples using filament extruded PE has managed to get the tensile modulus over 1 GPa whereas the samples using filament extruded samples have got tensile modulus value below 1 GPa. Sample HDPE_60 had lesser plastic content as compared to sample HDPE_70 so it had weaker bond. To be clearer, in Table 8 it can be seen that sample HDPE60_Comp got only 0.8647 GPa of tensile modulus while using the filler wire same as base materials and sample HDPE70_Comp got the tensile modulus value of 1.0515 GPa.

4.2 Background researches and comparisons

Joining of WPC by using hot gas welding technique is an emerging joining technique and still many researches yet to be done to identify its more possibilities and increasing efficiencies.

Rahbarpour et al. (2014) have proposed about welding of WPC (30% wood and 70% HDPE) by friction stir welding process. It has found that the joint of WPC seemed to be strongest while using the high level of rotational speed of 2000 rev/min and low travel speed of 8 mm/min. It had obtained the maximum tensile strength of 15.7 MPa, which was about 92.95% of the strength of base material having 16.89 MPa.

Meanwhile, in this experimental result, it has found the maximum tensile strength of 8.1470 MPa, which is only about 45.12% of the strength of base material having 18.0550 MPa. While using hot gas welding, it is very necessary to have a proper selection of filler wire as it should be completely melted or fused to the base materials. As compared to friction stir welded joint, hot gas welded joint lost most of its original strength. Thus, friction stir welding process seems to be more convincing than hot gas welding process to join WPCs in order to have good tensile strength.

In other experiment, Gfeller et al. (2003) have proposed about welding of wood by vibrational welding process in which the bonding of wood mainly caused due to the melting of lignin in wood. In that experiment, hard wood (beech) and softwood (Norway spruce) were used. Norway spruce did poor weldability as compared to beech. The tensile strength of welded joint mainly depended on the welding pressure and welding time. Higher the welding pressure, higher was the welded joint strength. Meanwhile, welding time did not have much influence on joint strength. In case of welded softwood or Norway spruce, it can be frictionally welded but the problem with such type of wood was the cell walls collapse. The highest tensile strength obtained was 7.61 MPa but still lesser than 10 MPa strength value which is required for structural wood joint according to EN205-D1 while the weakest joint of spruce wood was 0.5 MPa. After modifying some parameters like: welding time for 3 seconds and holding time for 5 seconds, the tensile strength for welded joint reached up to 10 MPa, which satisfied the EN205-D1.

As compared to this experiment, the maximum tensile strength of welded WPC reached to 8.1470 MPa which is little closer to 10 MPa. In case of WPC welding only plastic has got melted because lignin of wood has higher melting temperature than plastics. In future researches, studies can be done to enhance the joint strength of WPC because substituting the wooded welded structural joints would be good to moisture resistance or water absorption. Furthermore, melting of wood dusts should also be considered to enhance the welded joint strength of WPC.

M. Husain et al. (2015) have performed a test on friction stir welded polyamide (nylon 66) sheets having a tensile strength of 15.57 MPa of base material. It was proposed that tensile strength of welded polyamide increases and then decreases as increasing in rotational speed. It was concluded that there is an optimum rotational speed in friction welding procedure at which the welded joint achieves the optimum tensile strength. The maximum tensile strength of welded polyamide was 8.51 MPa at 1570 rotational speed and 42 mm/min of traverse speed. In friction stir welding, the main factors affecting welded joints are rotational speed and traverse speed.

In this research work, maximum welded joint strength (8.1470 MPa) was achieved while using the filler wire having the same composition as base materials, which seems promising as compared to welded polyamide. Although there are numerous factors to be considered while welding WPC like: plastic content in WPC, filler rod’s composition, temperature of hot gas and the experience of welder, welded WPC gave a tough strength comparison to the welded plastic or polyamide.

Bozkurt (2012) has come up with the study on optimizing the friction stir welding process parameters to achieve maximum tensile strength in polyethylene sheets. The research has adopted the Taguchi method to optimize the welding parameters. Three main parameters were analyzed, they are tool rotation speed, tool traverse speed and tilt angle. The tensile strength of base HDPE was 22.5 MPa. The maximum tensile strength of welded HDPE achieved was 19.4 MPa at 3000 rpm of tool rotation speed, 115 mm/min of tool traverse speed and tilt angle of 2°. In such welding parameters, no void nor crack were observed around the welded zone. Temperature variation between 120°C to 165°C was maintained whereas the melting temperature of HDPE is 132°C. Hence, the welding of HDPE is done by getting a molten state by heating the base materials.

Meanwhile, in this research, the tensile strength of base materials were 9.2274 MPa and 18.0550 MPa for HDPE_60 and HDPE_70 respectively. After the welding, their lowest strength value reached to 1.6134 MPa and 1.9707 MPa respectively while using the commercial PP as filler wire and their highest strength values reached to 5.8735 MPa for HDPE_60 and 8.1470 MPa for HDPE_70 while using the filament extruded filler wires. In comparison to welded HDPE, welded WPC lost a greater amount of tensile strength. In this research work, temperature was constant for every joints at about 140°C, which only melted the plastics but not the wood dust. Thus, the joint might not be equally strong as compared to welded plastics. Table 9 shows the comparison of maximum tensile strength of welded plastics, wood and WPC.

Table 9. Tensile strength of different materials (Rahbarpour et al. 2014, Gfeller et al. 2003, M. Husain et al. 2015, Bozkurt 2012)

Welded Materials	Welding Technique	Maximum Tensile Strength (MPa)
WPC (30% wood, 70% HDPE)	Friction Stir Welding	15.7
Wood hard wood (beech) and softwood (Norway spruce)	Vibration Welding	7.61
Polyamide (nylon 66) sheets	Friction Stir Welding	8.51
Polyethylene sheets	Friction Stir Welding	19.4
HDPE_70	Hot Gas Welding	8.1470

Table 9 shows that the plastic has the good weldability as compared to wood and WPC whereas hot gas welding technique shows the better result to join WPC as compared to vibration welding for joining the wood.

Comparison chart of welding procedures for different materials is shown in Figure 41

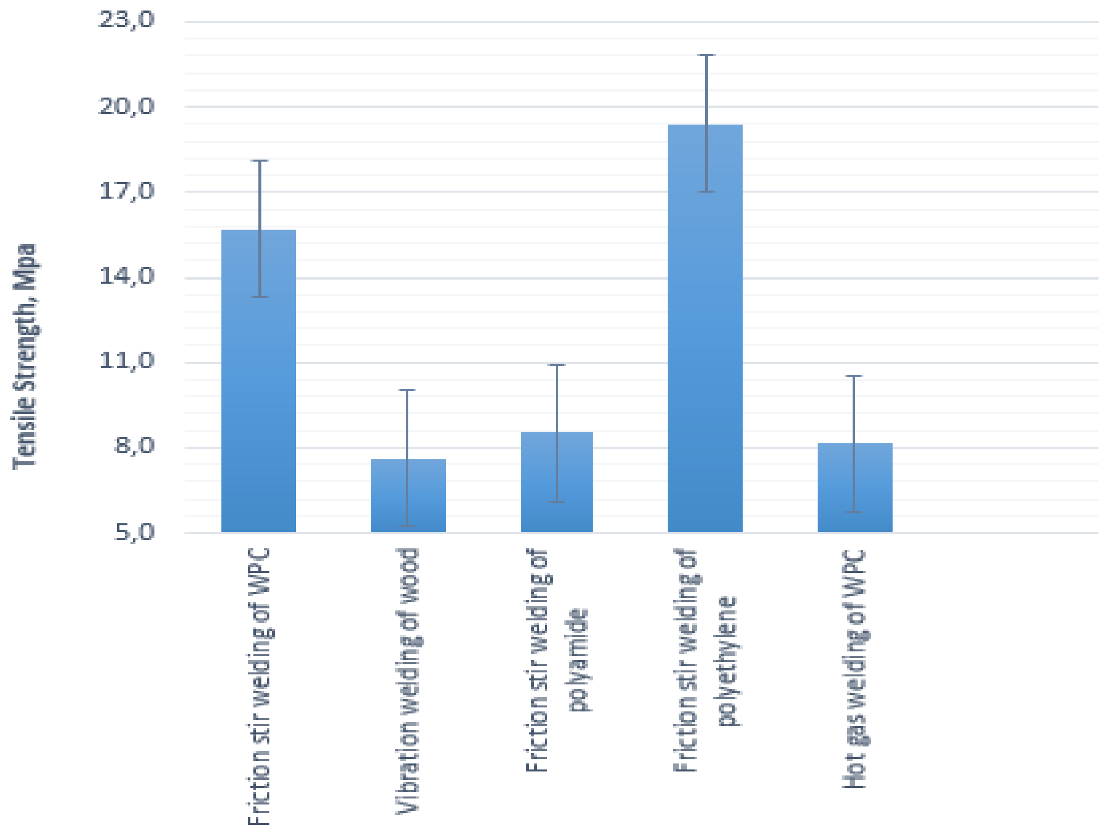

Figure 41. Tensile strength of different welded materials (Rahbarpour et al. 2014, Gfeller et al. 2003, M. Husain et al. 2015, Bozkurt 2012).

In Figure 41, it is seen that the friction stir welded polyethylene sheets has the highest and vibration welded wood has the lowest tensile strength among all welded materials. As compared to hot gas welding technique, friction stir welding process seems to be more appropriate welding process to join WPC. Friction stir welded WPC has almost double of tensile strength as of hot gas welded WPC.

Moreover, hot gas welded WPC has stronger welded joint than vibration welded wood. It can be said that due to the presence of plastic content in WPC, it has better weldability than wood. It can be said that welded WPC has much more convincing applications than welded wood. In other comparison, hot gas welded WPC has closer tensile strength to friction stir welded polyamide. There are many factors to be taken care while applying hot gas welding. With better care and perfectly fulfilling all the welding parameters, hot gas welding procedure is a good option to weld WPC and can improve its joint strength. Friction stir welded WPC has overcome on tensile strength to plastic also. It can said that with greater improvements welded WPC can be stronger than the welded plastics.

In another study, Balkan et al. (2008) have suggested that weldability of thermoplastics increase as the viscosity and activation energy of the joining materials decreases. For example, PP and PE have good weldability than PVC because they have lower viscosity values and activation energy than PVC thermoplastics. In case of WPC viscosity mainly depends upon the both wood quantity and its species (Li and Wolcott 2004, p. 310). Thus, proper selection of wood species having lower values of viscosity and thermoplastics like PP or PE would have the strongest weld joint. In this experimental text, spruce was used. So, for better weld quality wood type having lower viscosity than spruce types and thermoplastics like PP or PE and filler wire should be the same as base materials to give the strongest weld joint for any WPCs.

Furthermore, Balkan et al. (2008) have proposed higher the values the welding energy, higher will be the welded joint strength. In plastic welding, it was appeared to have stronger welded joint when they consumed greater values of welding energy. In double V-groove weld joints, they contained greater values of welding energy and joint seemed to be stronger.

In this experiment, single V-groove joint was adopted hence lesser values of welding energy required. It is thus can be assumed to have higher WPCs' weld strength if they contain double V-groove welds. It can be tested on further experiments.

4.3 Filler Wires Evaluation

From this experimental data, it can be seen that filament extruded (recycled) PP and PE filler wires containing 10% cellulose showed better result as compared to commercial PP and PE. Figure 42 shows the comparison chart of filament extrude filler wires and commercial filler rod based on the welded joint strength. Filler wires as same compositions to base materials are excluded from this figure.

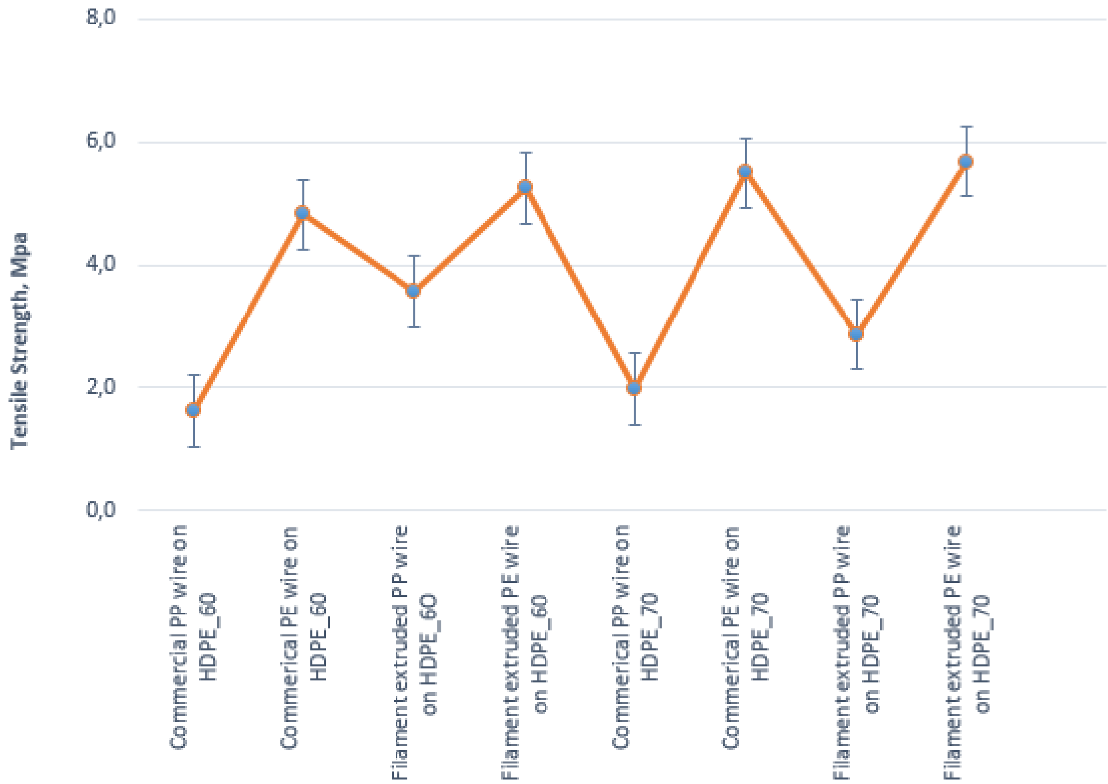

Figure 42. Filler wires comparison based on the welded joint strength.

From the Figure 42 it can be seen that filament extruded filler wire containing 10% cellulose showed the better result as compared to commercial filler wires. For instance, filament extruded PE filler rod on sample HDPE_70 showed the best result with 5.6802 MPa, as compared to other filler wires. Moreover, in sample HDPE_60, filament extruded PE wire also showed the good result with 5.2463 MPa as compared to commercial PE wire which has only 4.8173 MPa. In a similar way, filament extruded PP filler wires had managed to increase the tensile strength of welded joints as compared to commercial PP wires. The highest welded joint strength achieved on sample HDPE_60 is 3.5653 MPa, in which commercial PP wire showed the weakest joint with only 1.6134 MPa on the same sample. The main observation from Figure 42 can be seen that filament extruded PE wire managed to increase the welded joint strength by almost 33% as compared to the commercial PE wire. Table 10 shows the percent in loss of strength by WPC while using different filler wires.

Table 10 tensile strength of welded WPC in percent while using different filler wires

Filler wires	Tensile strength of welded WPC in percent (%) as compared to base material while using different filler wires	Loss in tensile strength by WPC in percent (%) as compared to base materials
Commerical PP in HPDE_60	17.44	82.56
Commercial PE in HDPE_60	52.22	47.78
Filament extruded PP in HDPE_60	38.67	61.33
Filament extruded PE in HDPE_60	56.88	43.12
Commercial PP in HDPE_70	10.90	89.10
Commercial PE in HDPE_70	30.39	69.61
Filament extruded PP in HDPE_70	15.84	84.16
Filament extruded PE in HDPE_70	31.45	68.55
Filler wire same as sample HDPE_60	63.59	36.41
Filler wire same as sample HDPE_70	45.12	54.88

Table 10 shows that maximum amount of tensile strength is lost by sample HDPE_70 with 89.10% while using commercial PP as a filler wire. As base material had HDPE plastic, PP filler wire didn’t diffuse to base materials. Those plastics have different melting temperatures. For example: commercial PP has about 160°C of melting temperature whereas HDPE has about 180°C. Thus, hot gas was unable to melt both the materials at the same time and diffusion did not occur hence giving a weak bond. Every samples using commercial PP filler wire showed huge amount of strength loss as compared to base materials’ strength. In a similar way, samples using filament extruded PE wires containing 10% cellulose lost lesser amount of tensile strength as compared to samples using commercial PE filler wires.

Furthermore, from table 10 it is seen that samples using filler wires as same compositions to base materials have lost the lesser amount of tensile strength as compared to all welded samples. To be clearer, sample HDPE_60 has lost only 36.41% of tensile strength which is the lowest lost value among all samples. Moreover, HDPE_70 has lost 54.88% of its tensile strength of base materials but still it has the highest welded tensile strength as its base material has the highest tensile strength. From this data, it can be said that filler wire should be as same composition as of base materials to join WPC while using hot gas welding technique to make tensile strength of welded joint as maximum as possible.

4.4 Scanning Electron Microscopy (SEM) analysis

In SEM high-energy electrons are focused on the surface of test specimens to observe the external morphology, chemical composition, different orientations of materials of the specimen and visualized them in a 2-dimensional image. Test specimen and sample setup are illustrated in Figure 43 and 44 respectively.

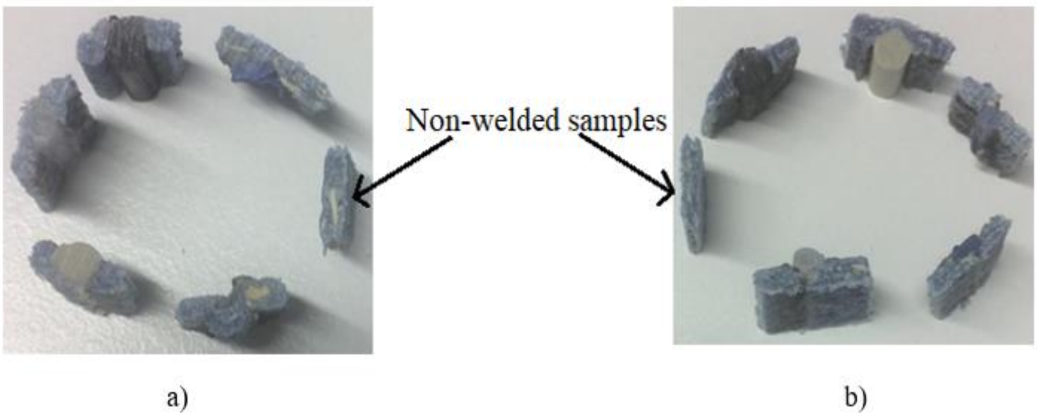

Figure 43. Test samples for SEM analysis a) HDPE_60 specimen and b) HDPE_70 specimen.

Figure 44. Test specimen setup for SEM analysis

In this research, crystalline structure of the samples were examined by using SEM testing on the welded area. Figure 45 depicts the weakest welded joint. It was a sample HDPE60_PP using a commercial PP as filler wire. In SEM, it can be seen easily a boundary line between filler wire and base materials meaning intermolecular fusion was not strong and non-uniformly distributed. In this sample, filler wire had higher melting temperature than base materials thus thin plate WPCs melted faster than the filler rod and it did not melt completely into the surface of base materials.

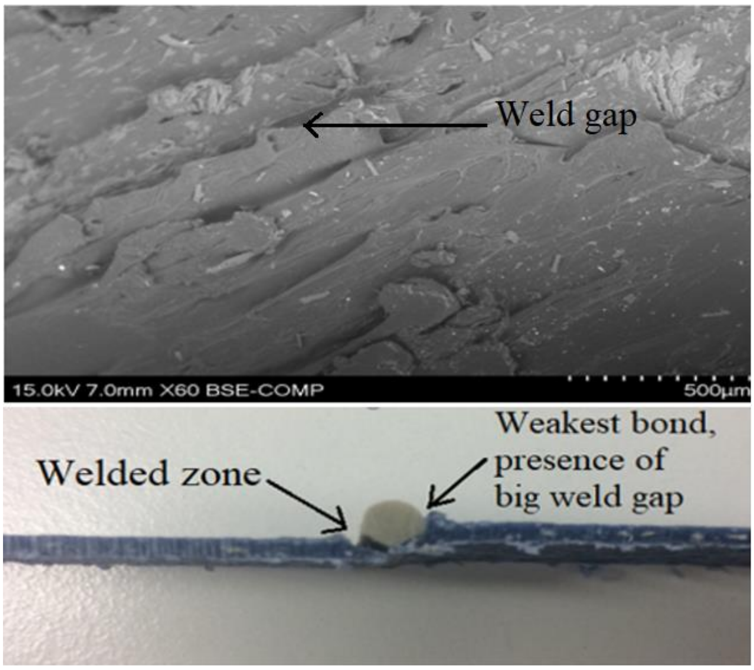

Figure 45. Welded joint and SEM picture of sample HDPE60_PP with pure PP filler wire and in magnifications x60

Figure 46 is about the sample HDPE70_PE and used commercial PE as filler rod. In this case tensile strength was about moderated as not strong bond was formed. In SEM, boundary between filler rod and base WPCs can be seen meaning uniform bonding was not formed.

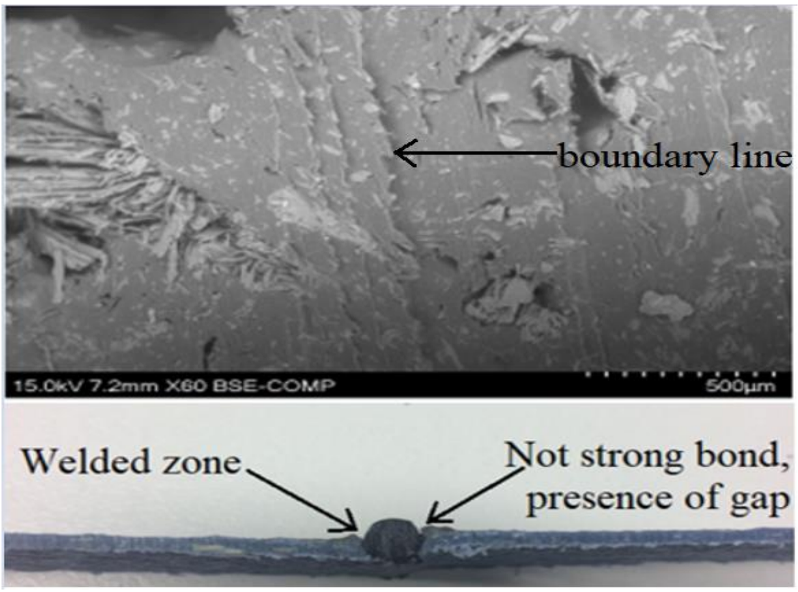

Figure 46. Welded joint and SEM picture of sample HDPE70_PE with pure PE filler wire in magnifications x60

Furthermore, SEM picture of HDPE70_Comp sample, which had same filler wire as base materials, is shown in Figure 47. Among the welded workpieces, this sample had the strongest bond having tensile strength of 8.1470 MPa while non-welded HDPE_60 (HDPE with 60% PE) sample had tensile strength of 9.2 MPa. In SEM analysis, border between filler wire and base materials was hard to identify as strong bond was obtained.

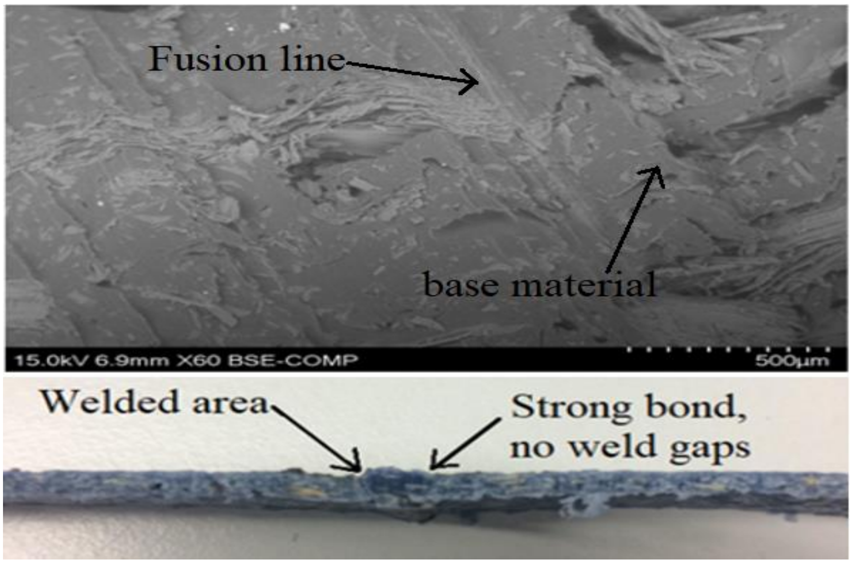

Figure 47. Welded joint and SEM picture of sample HDPE70_Comp in magnifications x60

Moreover, sample HDPE70_RecPP with filament extruded PP filler wire with 10% cellulose is shown in Figure 48. This sample showed the weakest weld joint with 2.8641 MPa while using the filament extruded filler wires but still it showed the greater tensile strength as compared with the same sample while using the commercial PP having 1.9707 MPa. In SEM, some cellulose can be seen and boundary line too. It did not show a uniform and perfect bond.

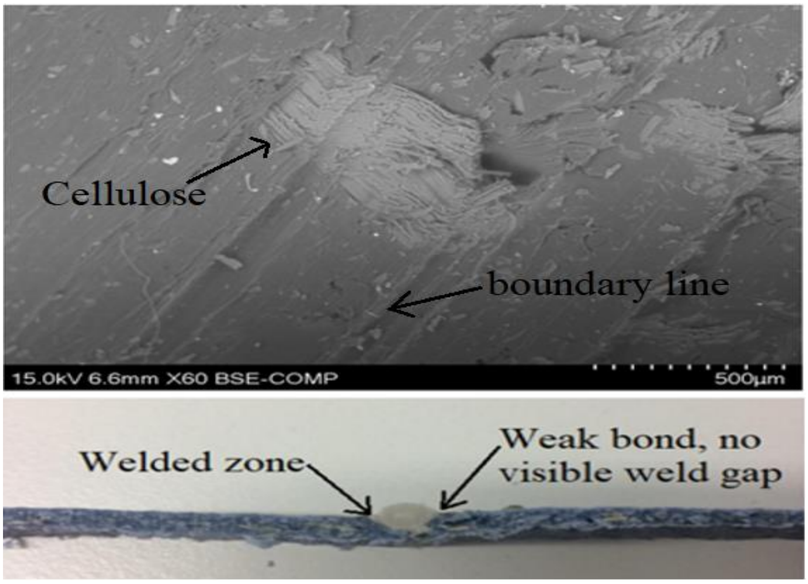

Figure 48. Welded joint and SEM picture of sample HDPE70_RecPP in magnifications x60

Figure 49 shows the SEM test of sample HDPE70_RecPE (HPDE with 70% PE and filament extruded PE filler wire with 10% cellulose. This sample showed the strongest welded joint among the samples that used filament extruded filler wire with 5.6802 MPa. In SEM, it is seen some cellulose hard to identify the boundary line. The fusion was good, and intermolecular bonding was strong.

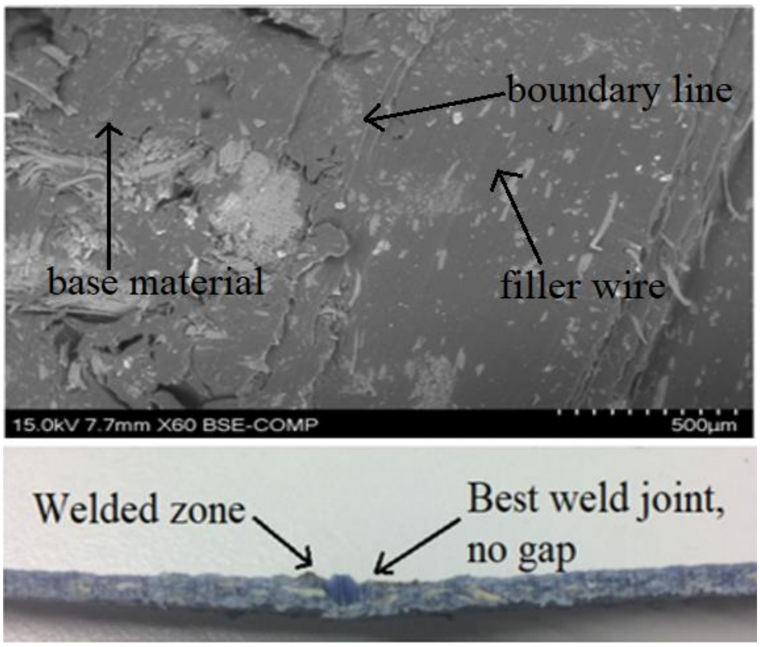

Figure 49. Welded joint and SEM picture of sample HDPE70_RecPE in magnifications x60

Figure 50 shows the SEM pictures of sample HDPE_60 containing 60% HDPE and sample HDPE_70 containing 70% HDPE in a) and b) respectively. Both samples were non-welded. In both samples, holes or cracks can be detected as it could be the manufacturing defect, or the wood flour and plastics did not mix well enough. Having non-welded structure, it was obvious for them to have good tensile strength. HDPE_70 sample had the highest tensile strength among all the samples with 18.0550 MPa and HDPE_60 with tensile strength of 9.2274 MPa.

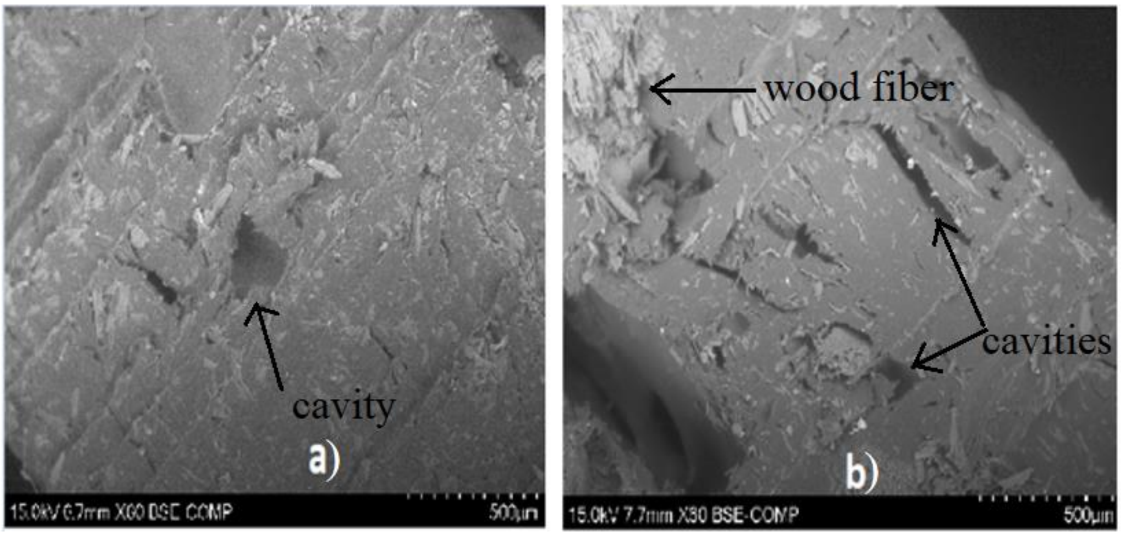

Figure 50. SEM picture of samples **a**) HDPE_60 and **b)** HDPE_70 in magnifications x60

4.5 Focus on Improvements

Joining of WPC by using hot gas welding technique is entirely a growing trend and many researches or experiments to achieve more efficiency, reliable joint strength has still yet to be done. In this research work, major hot gas welding parameters have been ignored such as well-experienced welder, proper surface finishing or cleaning, lack of proper fixtures, proper welding speed and deposition rate of filler wire. These factors might have greatly hindered on joint strength of welded WPC.

Lack of proper cleaning of welding surfaces might have caused some contaminations or airs to be captured in welded areas, which might have caused to form a weak joint. They can cause a vacuum or weld gap in the joint.

Moreover, proper care of part fixturing was one of the greatest lacks of this research work. Hot gas welding causes part distortion due to heat causing the parts to create more gap in welding zone as shown in Figure 51. In this experiment also, work parts have distorted and created a noticeable gap between the weld joints. This might have surely caused to form weak welded joints.

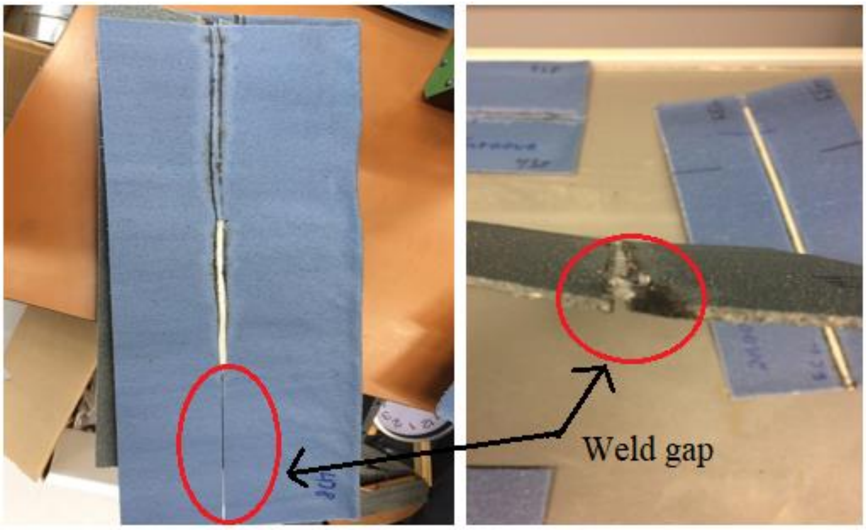

Figure 51. Base materials' gap due to lack of fixture.

Moreover, welding temperature was constant to every filler wires, which seemed to be unfavorable because different filler wires had different melting temperature based on their composition. Therefore, some filler wire melted completely in the weld area. For instance, filament extruded PE, which had the lowest melting temperature and melted completely on the welding joints as shown in Figure 52 (a). On the other hand, commercial PP did not melt completely on the weld zone as it had higher melting temperature as shown in Figure 52 (b). Such type of error can hinder in forming a good weld strength.

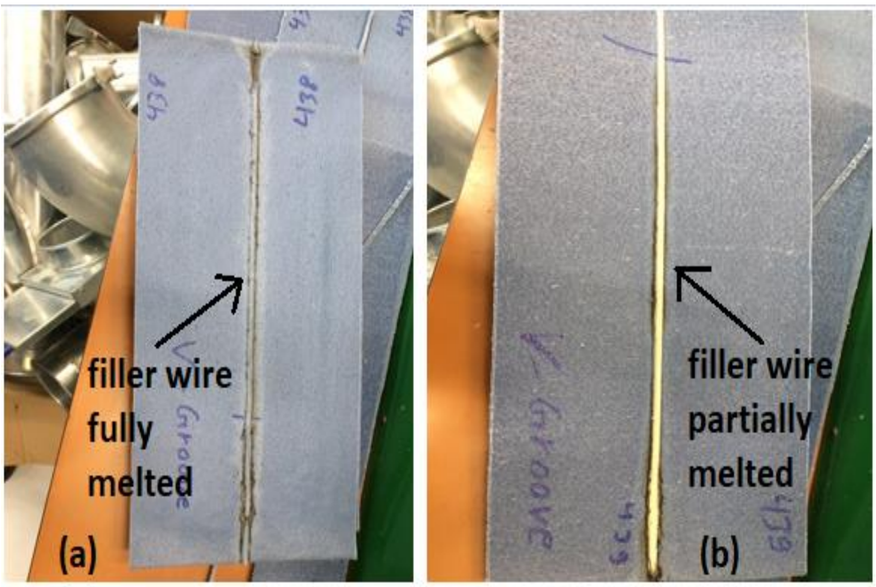

Figure 52. (a) Filler wire completely melted on base material (b) filler wire partially melted on base material.

As notified earlier, ignorance on welding speed and deposition rate might have somehow crippled the welded joint. Proper welding speed enhance the proper deposition rate of filler rod on the base materials. Slow welding speed causes more deposition of filler wire while fast welding speed causes less deposition of filler wire. Figure 53 illustrates the non-uniform deposition rates of filler wire on base materials. In this experiment, sometimes more deposition and sometimes less deposition of filler wire was notified, as the welding speed was not constant. Both cases are not suitable to achieve reliable joint strength.

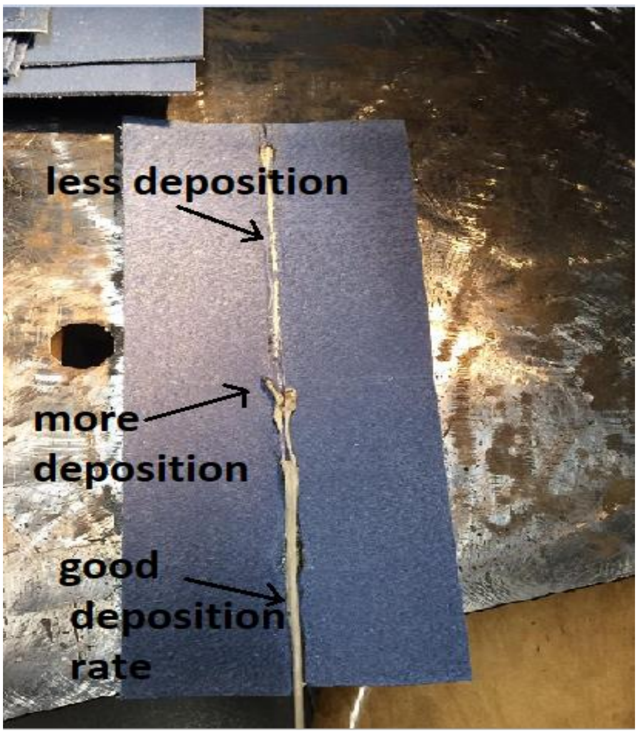

Figure 53. Variation in deposition rate of filler wire.

4.6 Possibilities of welded WPC

From this research work, it is observed that the welded WPC has lost its original tensile strength by 36.41% at the minimum, which is not very satisfying. By losing most of its strength, using of welded WPC structures is still questionable. Welded structures should exhibit the closer strength value as of base materials otherwise there would not be safe to use the welded structures if not fulfilling the minimum structural strength value. So, different new techniques, methods, analyzing different factors should be done to enhance the tensile strength in welded joints as much as possible.

Moreover, from this test it is very clear that the filler wire should be as same composition as of base materials to achieve greatest tensile strength as much as possible. Thus obtaining as much strength from welded WPC while using same filler wire as of base materials should be further researched or examined in detailed.

5 CONCLUSION

Amount of plastics presence in WPC greatly effect on its weldability and weld strength. Greater the plastics percentage in WPC, greater will be the weld joint strength. The main target of this research was to identify the strength of welded WPC after using various filler wire types for the specific base materials. Five different types of filler rods were used. To test the mechanical property, tensile tests were done. Moreover, SEM test was done to study the morphology of the welded joint.

One of the main things discovered from this experimental work from the viewpoint of filler wires is that the recycled filler (filament extruded PP and PE) wires did show good results as compared to commercial filler wires. The result showed that filament extruded PE wire managed the increase the welded joint strength by almost 33% as compared to the commercial PE wire. It gives an encouragement to use more recycled plastic wastes than using virgin materials.

The strength of welded joint greatly depended on the type of plastics, its amount in WPC and on the filler wire. The experiment showed that the nonmatching filler wire gave the weakest joint strength, like: commercial PP wire with HDPE_ 60 and HDPE_70 samples. In those cases, base materials melted faster than filler wires causing them deformed or overheating of WPCs.

On the other hand, commercial PE did a better weld as compared to commercial PP. Using same commercial plastic type on both the base materials and filler wires, joint was good but still not so strong as compared to filament extruded PP and PE containing 10% cellulose. Anyway, filament extruded PP still showed weak bond as compared to filament extruded PE. The strongest weld bond as achieved by using the same filler wire as of base materials. Having lower percentage of plastic content, still HDPE_60 sample having 60% plastic content showed weak bond in the case as compared to HDPE_70 sample with 70% plastic content. The loss of tensile strength by WPC also one of the findings in this study. In case of HDPE_60 sample, it lost its tensile strength by almost half of the original (non-welded) sample. In a similar way, HDPE_70 lost its tensile strength by almost more than a half of its non-welded structure.

The field of applications of WPC is increasing thus numerous products are being manufactured so does the repairing of its broken parts and its wastes. It is always better to repair and reuse rather than decomposing at the first damage. Joining broken or damaged WPC parts could be done if it can only withstand the further load, negative environmental influences, like: sudden impact, overloading. However, this research showed the WPC structures lose its tensile strength when welded so it would be a wise decision to avoid welding WPC parts.
Finally, this experiment only relied on joining WPC with different filler wires avoiding various important factors for proper welded joint strengths, like:

- Skilled welder
- Welding speed and deposition rate
- Surface preparation and cleanliness
- Part fixturing
- Welding temperature should be considered based on filler rods' compositions.

These factors need to be properly considered to have good quality of welded joints. Failing to fulfill one factor can weaken the joint and its strength. Focusing those factors and performing new researches could develop greater possibilities on joining of WPC with the hot gas welding technique.

Different welding processes have their own working techniques and specialties. Some welding processes need less equipment while some processes may require advanced machineries. Anyway, the welding process is mainly about melting the base materials and filler wire (if used). Temperature should be maintained in such a way that the components of materials (base material and filler rod) should be completely melted. If all the components get melted, stronger bond will be formed as they cool down. In case of WPC, plastic and wood flour has different melting temperatures. Plastic particles melt faster as compared to wood fiber or lignin. So, bonding occurs between plastics around the weld zone whereas the wood fiber remains non-melted and thus bonding doesn't occur between wooden fibers. This could be the main reason of WPC for not getting the strongest welded joint as expected. In a similar way, in this experiment, hot gas welding mechanism solely melted the plastics of the base materials and the filler rods. Thus, hot gas welding process gave just around 63.59% of the strength of base material to the welded joint, which is not so overwhelming. Several researches and experiments still need to be done to increase its effectiveness.

LIST OF REFERENCES

Amancio-Filho, S. and dos Santos, J. 2009. Joining of polymers and polymer-metal hybrid structures: Recent developments and trends. Polymer Engineering & Science, 49(8), pp.1461-1476.

Andre, S. 2011. Wood Plastic Composites (WPCs) as an Alternative to Solid Lumber. [web document] pp.17-19. [Accessed 13 Nov. 2018]. Available: https://open.library.ubc.ca/cIRcle/collections/undergraduateresearch/52966/items/1.0103128

Atozplastics. 2003. High performance additives-essential for success of wood plastic composites (WPC), [web document] [Accessed 13 Nov. 2018]. Available: http://atozplastics.com/upload/Literature/High-performance-additives-for-wood%20plastic-composites-WPC.asp

AZoM. 2017. An Introduction to Single Screw Extrusion. [web document]. [Accessed 13 Nov. 2018]. Available: https://www.azom.com/article.aspx?ArticleID=13566

Balkan, O., Demirer, H., Ezdeşir, A. and Yıldırım, H. 2008. Effects of welding procedures on mechanical and morphological properties of hot gas butt welded PE, PP, and PVC sheets. Polymer Engineering & Science, 48(4), pp.732-746.

Baudrit, B., Bogdanovic, M., Heidemeyer, P. and Bastian, M. 2011. Hot plate welding of wood plastic composites based on polyvinylchloride and polypropylene. Wuerzburg: ANTEC, pp.2-10.

Bozkurt, Y. 2012. The optimization of friction stir welding process parameters to achieve maximum tensile strength in polyethylene sheets. Materials & Design, 35, pp.440-445.

Crawford, R. 2002. Plastics engineering. Oxford: Butterworth-Heinemann, pp.1-4.

Das, O., Sarmah, A. and Bhattacharyya, D. 2015. A sustainable and resilient approach through biochar addition in wood polymer composites. Science of The Total Environment, 512-513, pp.326-336.

DEMS Oman. 2016. Your Partner for Thermoplastics and Geosynthetics. Know How: Understand the Basics of Plastic Welding. . [Accessed 28 Aug. 2018]. Available: https://www.dems-oman.com/leister-plastic-welding/welding-methods/

Directindustry.com 2018. HV-15-Hot plate welding machine | ac | automatic | for plastics by Branson Ultrasonics | DirectIndustry. [web document], [Accessed 26 Nov. 2018]. Available: http://www.directindustry.com/prod/branson-ultrasonics/product-5555-809061.html#product-item_1950570

Ecoursesonline.iasri.res.in. 2013. Design of Structures: LESSON 7. Welded Connection. [web document]. [Accessed 27 Nov. 2018]. Available: http://ecoursesonline.iasri.res.in/mod/page/view.php?id=127486

Fasce, L., Cisilino, A., Frontini, P., Marczis, B. and Czigany, T. 2007. Failure characterization of polypropylene block copolymer welded joints. Polymer Engineering & Science, 47(7), pp.1062-1069.

Frantz, J. 2013. How to Select a Plastics Assembly Process. [web document]. [Accessed 27 Aug. 2018]. Ptonline.com. Available: https://www.ptonline.com/articles/how-to-select-a-plastics-assembly-process

Friedrich, D. and Luible, A. 2016. Investigations on ageing of wood-plastic composites for outdoor applications: A meta-analysis using empiric data derived from diverse weathering trials. Construction and Building Materials, 124, pp.1142-1152.

Fxi. 2018. RF Welding Foam - FXI Technologies. [web document]. [Accessed 27 Aug. 2018]. Available: http://fxi.com/foam-technologies/processes/rf-welding.php

Gfeller, B., Zanetti, M., Properzi, M., Pizzi, A., Pichelin, F., Lehmann, M. and Delmotte, L. 2003. Wood bonding by vibrational welding. Journal of Adhesion Science and Technology, 17(11), pp.1573-1589.

Goodship, V. 2007. Introduction to plastics recycling. 2nd ed. Shawbury, U.K.: Smithers Rapra, p.12.

Gouda, O., Thabet, A., Mobarak, Y. and Samir, M. 2014. Nanotechnology Effects on Space Charge Relaxation Measurements for Polyvinyl Chloride Thin Films. International Journal on Electrical Engineering and Informatics, 6(1), pp.1-12.

Grewell, D. and Benatar, A. 2009. Comparison of orbital and linear vibration welding of thermoplastics. Polymer Engineering & Science, 49(7), pp.1410-1420.

Grewell, D., Benatar, A. and Park, J. 2003. Plastics and composites welding handbook. Munich: Hanser Gardener.

Haque, M. and Siddiqui, M. 2016. Plastic Welding: Important Facts and Developments. American Journal of Mechanical and Industrial Engineering, 1, pp.15-19.

Hempel, P. 2016. Constitutive modeling of amorphous thermoplastic polymers with special emphasis on manufacturing processes. p.33.

Hietala, M. 2011. Extrusion processing of wood raw materials for use in wood-polymer composites. Luleå: Luleå tekniska universitet, p.3.

Huang, Y. 2012. Study on Design of Welding-Joint and Structure of Welding Based on Ultrasonic Welding Technology. Applied Mechanics and Materials, 101-102, pp.871-875.

Humbe, A., Deshmukh, P., Jadhav, C. and Wadgane, S. 2014. Review of Laser Plastic Welding Process. Impact: International Journal of Research in Engineering and Technology (IMPACT:IJRET), [web document] pp.191-206. [Accessed 27 Aug. 2018]. Available: http://oaji.net/articles/2014/489-1393938157.pdf

Inkwood Research. 2017. Europe Wood Plastic Composites Market Share, & Forest 2018-2026. [web document]. [Accessed 13 Nov. 2018]. Available: https://www.inkwoodresearch.com/reports/europe-wood-plastic-composites-market/

John, V. 1983. Introduction to Engineering Materials. 3rd ed. London, p.231.

Kagan, V. and Nichols, R. 2004. Recent Advances and Challenges in Induction Welding of Reinforced Nylon in Automotive Applications. [web document]. [Accessed 13 Nov. 2018]. Available at: http://www.emabond.com/PDF/SAE%20Paper%20Emabond%20Process.pdf

Kallee, S. 2000. Development of low cost linear friction welding machines-Case Study 20. [web document]. [Accessed 26 Nov. 2018]. Available: https://www.twi-global.com/news-events/case-studies/development-of-low-cost-linear-friction-welding-machines-020/

Kim, J. and Pal, k. 2011. Recent advances in the processing of wood-plastic composites. Berlin: Springer

Kim, S. and Somorjai, G. 2006. Surface science of single-site heterogeneous olefin polymerization catalysts. Proceedings of the National Academy of Science, 103(42), pp. 15289-15294.

Koay. S., Subramanian, V., Chan, M., Pang, M., Tsai, K. and Cheah, K. 2018. Preparation and Characterization of Wood Plastic Composite Made Up of Durian Husk Fiber and Recycled Polystyrene Foam. MATEC Web of Conferences, 152, p.02019.

Kunststoffe. 2013. nova-Institute Publishes Study on WPC. [web document]. [Accessed 13 Nov. 2018]. Available: https://www.kunststoffe.de/en/news/overview/artikel/nova-institute-publishes-study-on-wpc-708506.html

Li, T. and Wolcott, M. 2004. Rheology of HDPE–wood composites. I. Steady state shear and extensional flow. Composites Part A: Applied Science and Manufacturing, 35(3), pp.303-311.

Lu, J., Wu, Q. and McNabb, Jr, H. 2000. Chemical Coupling in Wood Fiber And Polymer Composites: A Review of Coupling Agents and Treatments. Wood and Fiber Science, [web document]. [Accessed 12 Sep. 2018]. Available: https://www.researchgate.net/publication/280136866_Chemical_coupling_in_wood_fiber_and_polymer_composites_A_review_of_coupling_agents_and_treatments

M. Husain, I., K. Salim, R., Azdast, T., Hasanifard, S., M. Shishavan, S. and Eungkee Lee, R. 2015. Mechanical properties of friction-stir-welded polyamide sheets. International Journal of Mechanical and Materials Engineering, 10(1).

Maier, C. and Calafut, T. 1998. Polypropylene. Norwich, NY: Plastics Design Library, p.1.

Marczis, B. and Czigány, T. 2006. Interrelationships between welding parameters of hot-gas welded polypropylene. Polymer Engineering & Science, [web document] 46(9), pp.1173-1181.

Mingareev, I., Weirauch, F., Olowinsky, A., Shah, L., Kadwani, P. and Richardson, M. (2012). Welding of polymers using a 2µm thulium fiber laser. Optics & Laser Technology, 44(7), pp.2095-2099.

Mwema, M., Mburu, N., Mutunga, N. and Kalama, F. 2015. Development of Wood-Plastic Composite at Dedan Kimathi University of Technology, Kenya. Engineering Research and Applications, 5(12), pp.11-17.

Ngaowthong, C., Rungsardthong, V. and Siengchin, S. 2016. Polypropylene/hemp woody core fiber composites: Morphology, mechanical, thermal properties, and water absorption behaviors. Advances in Mechanical Engineering, 8(3), p.1-10.

Niska, K. and Sain, M. 2008. Wood-polymer composites. Cambridge: Woodhead Pub.

Park, S. and Kim, S. 2014. Poly (ethylene terephthalate) recycling for high value added textiles. Fashion and Textiles, 1(1).

Patham, B. and Foss, P. 2011. Thermoplastic vibration welding: Review of process phenomenology and processing-structure-property interrelationships. Polymer Engineering & Science, 51(1), pp.1-22.

Patil, R., Tang, J., Berrios, J., Pan, J. and Swanson, B. (2005). Physical Characteristics of Food Extrudates - A Review. In: ASAE Annual International Meeting. Tampa, Florida: The Society for Engineering in agricultural, food, and biological systems, P.2.

Peacock, A. 2000. Handbook of polyethylene. New York, N.Y.: Dekker, pp.2-4.

Polymaterial. 2013. Poly Material Service Inc. [web document]. [Accessed 31 Aug. 2018]. Available: http://www.polymaterial.net/wpcs

Potente, H., Karger, O. and Fiegler, G. 2002. Laser and Microwave Welding-The Applicability of New Process Principles. Macromolecular Materials and Engineering, 287(11), pp.734-744.

Ragaert, K., Delva, L. and Van Geem, K. 2017. Mechanical and chemical recycling of solid plastic waste. Waste Management, 69, pp.24-58.

Rahbarpour, R., Azdast, T., Rahbarpour, H. and Shishavan, S. 2014. Feasibility study of friction stir welding of wood–plastic composites. Science and Technology of Welding and Joining, 19(8), pp.673-681.

Rajendran, S., Scelsi, L., Hodzic, A., Soutis, C. and Al-Maadeed, M. 2012. Environmental impact assessment of composites containing recycled plastics. Resources, Conservation and Recycling, 60, pp.131-139.

Raut, R. 2016. The next generation of portable bevelling. [web document]. [Accessed 3 Aug. 2018]. Available: https://www.thefabricator.com/article/powertools/the-next-generation-of-portable-beveling

Reddy, A. 2015. Welding of Plastics. [web document]. Slideshare.net. [Accessed 29 Aug. 2018]. Available: https://www.slideshare.net/AshishReddy5/welding-of-plastics-47408268

Ropers, S. 2016. Bending Behavior of Thermoplastic Composite Sheets. p.6.

Roychoudhury, A., Sharma, V. and Singh, B. 2012. Microwave Welding: A New Tool for Welding of Thermoplastics. Mechatronics and Intelligent Manufacturing. 3, pp.85-93.

Saki, T. 2015. Reactive melt blending of low-density polyethylene with poly (acrylic acid). Arabian Journal of Chemistry, 8(2), pp.191-199.

Sass, J., Castleman, B. and Wallinga, D. 2005. Vinyl Chloride: As Case Study of Data Suppression and Misrepresentation. Environmental Health Perspective, 113(7),pp.809-812.

Seaman, G. 2012. Plastics by the Numbers. [web document]. Eartheasy Guides & Articles. [Accessed 21 Jul. 2018]. Available at: https://learn.eartheasy.com/articles/plastics-by-the-numbers/

Seretis, G., Manolakos, D. and Provatidis, C. 2018. On the graphene nanoplatelets reinforcement of extruded high density polyethylene. Composites Part B: Engineering, 145, pp.81-89.

Shen, L., Li, J., Li, R., Lin, H., Chen, J. and Liao, B. 2018. A new strategy to produce low-density polyethylene (LDPE)-based composites simultaneously with high flame retardancy and high mechanical properties. Applied Surface Science, 437, pp.75-81.

Stavrov, D. and Bersee, H. 2005. Resistance welding of thermoplastic composites-an overview. Composites Part A: Applied Science and Manufacturing, 36(1), pp.39-54.

Stokes, V. 1988. Analysis of the friction (spin)-welding process for thermoplastics. Journal of Materials Science, 23(8), pp.2772-2785.

Teodorescu-Draghicescu, H., Scarlatescu, D., Vlase, S., Scutaru, M. and Nastac, C. 2018. Advanced high-density polyethylene used in pipelines networks. Procedia Manufacturing, 22, pp.27-34.

The Welding Master. 2017. Different Types of Welding Joints - The Welding Master. [web document]. [Accessed 27 Nov. 2018]. Available: http://www.theweldingmaster.com/types-welding-joints/

Troughton, M. 2008. Handbook of plastics joining. Norwich, NY: William Andrew, pp.73-79.

TutorVista. 2018. Polypropylene. [web document]. [Accessed 21 Jul. 2018]. Available: https://chemistry.tutorvista.com/analytical-chemistry/polypropylene.html

Twi-global. 1996. Joints take 10 seconds in the microwave. [web document]. [Accessed 27 Aug. 2018]. Available: https://www.twi-global.com/news-events/connect/pre-1998-articles/1996-articles/joints-take-10-seconds-in-the-microwave/

Twi-global. 2018. Design-part 3 - Job Knowledge 92. [web document]. [Accessed 3 Aug. 2018]. Available: https://www.twi-global.com/technical-knowledge/job-knowledge/design-part-3-092/

Typesofweldingprocess. 2018. Ultrosonic welding method | principle | diagram | advantages | application. [web document]. [Accessed 27 Aug. 2018]. Available: http://www.typesofweldingprocess.com/ultrasonic_welding.html

Veethahavya, K., Rajath, B., Noobia, S. and Kumar, B. 2016. Biodegradation of Low Density Polyethylene in Aqueous Media. Procedia Environmental Sciences, 35, pp.709-713.

Weld Guru. 2018. Welding Methods and Techniques: Illustrations and Descriptions – Weld Guru. [web document]. [Accessed 25 Nov. 2018]. Available: https://weldguru.com/welding-methods/

Yoshioka, T., Kameda, T., Grause, G., Imai, S. and Okuwaki, A. 2009. Effect of compatibility between solvent and poly(vinyl chloride) on dechlorination of poly(vinyl chloride). Journal of Polymer Research, 17(4), pp.489-493.

Zhao, H., Zhou, Y., Zhu, H. and Wang, Q. 2011. Ultrasonic Welding Performance Analysis of Wood-Flour/PP Composites. Advanced Materials Research, 183-185, pp.2288-2292.