Chapter 17
Processability of Wood Fibre-Filled Thermoplastic Composite Thin-Walled Parts Using Injection Moulding

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Abstract A review of research on injection-moulded wood fibre-filled thermoplastic composites is presented in this chapter. Brief description of injection-moulding compounding process (including drying and mixing and extrusion) as well as injection-moulding process itself is also presented. A review on wood fibre-reinforced thermoplastic composites is also reported. An in-depth discussion is presented on thin-part moulding and the formation of residual stresses, volumetric shrinkage and warpage using injection moulding for composite products. Simulation work and statistical analysis related to the topic are also reviewed. Finally, some ideas about further research on wood-filled thermoplastic composite are proposed.

Keywords Wood polymer composites • Thin-walled part • Injection moulding • Residual stresses • Shrinkages • Warpage

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17.1   Introduction

Composites have become very important materials in the recent years due to advantages that they offered including light weight, part integration, comparable stiffness and strength properties to some metals and corrosion resistant (Sapuan and Abdalla 1998; Hambali et al. 2009, 2010). They have been widely used in many industries such as automotive, construction, marine, furniture, aerospace, telecommunications and sport industries. The development of green-composite engineering materials made from natural resources has rapidly increased in product development and manufacturing today due to people's awareness concerning environmental issues (Bachtiar et al. 2010; Leman et al. 2008; Rashdi et al. 2009; Ishak et al. 2010; Sapuan et al. 2005). Wood residue resources have a high potential for use as fillers in producing green composites, which have been extensively investigated over the past few years. However, limited research efforts were conducted on the processability and quality of parts after processing, especially in the injection-moulding process.

Processed natural fibres that are ready for compounding can be categorized into two categories: fibres and particulates. The difference between the two types can be noticed by the ratio of the length to diameter (normally known as aspect ratio) of the fibres. Particulates generally have fibre aspect ratio close to unity. For this type of fibre, generally strengthening mechanism is almost nonexistence; however, it has demonstrated good stiffness properties. Fibres can be short or long depending on whether or not the fibres are in the form of particulates or continuous fibres. This fibre exhibits more significant strengthening and has the potential to replace conventional fibres such as glass fibres as reinforcement in thermoplastic composites.

Thermoplastic materials are more promising than thermoset materials because of their lower melting point and they have greater potential to be recycled (Sanadi et al. 1998). The low melting points are necessary to minimize the fibre degradation when exposed to heat during the manufacturing processing (Sanadi et al. 1998). Therefore, the suitability of polymers as matrices for natural fibre depends on the thermal stability properties. Bledzki and Gassan (1999) showed that polyethylene (PE) and polypropylene (PP) are the most suitable compounds with wood flour/fibre, whose processing temperature does not exceed 230 °C.

17.2   Wood Fibre-Reinforced Thermoplastic Composites

Natural fibres are normally demonstrated comparable specific properties to conventional fibres like glass fibres, abundantly available and generally biodegradable that can be used to achieve durability without using toxic chemicals (El-Shekeil et al. 2012; Suriani et al. 2007; Sastra et al. 2006; Ishak et al. 2012; Yusoff et al. 2010). Furthermore, natural fibre thermoplastic composites can be used as alternatives to conventional fibre composites. They can be regarded as environmentally friendly

materials. They are also known as 'eco-composites' or 'green composites', which is suitable for semi- or nonstructural applications.

From a technical viewpoint, natural fibre-reinforced thermoplastic composites exhibit higher specific strength and stiffness than glass, reduced material weight and specific weight, high dimensional stability and high possible filling levels and are nonabrasive in nature. From an ecological viewpoint, natural fibre thermoplastic composites offer low cost, safe fibre handling, unlimited sources, low energy consumption, a wide variety of fibre types (i.e. wood, kenaf, bamboo, etc.), biodegradability and annual renewability. The future prospects of wood-reinforced thermoplastic composites are generally determined by many parameters such as customer requirements, introduction of newer products, high-quality components and research and development findings that act as inputs to these factors. In addition, products being produced must be affordable, recyclable and environmentally friendly (Ishak et al. 2010).

According to La Mantia and Morreale (2011), wood flour and fibres have been widely used reinforcements in polymer composites. Wood flour can be made available at low cost and in abundance from sawmill wastes after undergoing sieving process. Wood fibres were normally obtained from thermo-mechanical processing of sawmill wastes. Other important features of wood flour and fibres include dimensional stability and good stiffness properties. However, they suffered from some drawbacks such as low-strength and poor impact properties, poor matrix and filler or fibre bonding and thermal decomposition at temperatures above 200 °C (Netravali and Chabba 2003; Carroll et al. 2001).

Li and Wolcott (2004) studied the behaviour of high-density polyethylene (HDPE) wood fibre composites with two different filler loadings (40 and 60 wt.%) and two different types of wood (maple and pine) using capillary rheometer. They found that wall slip phenomena existed and they were mainly related to filler loadings. The analysis of flow material flow showed that the viscosity depended mainly upon the filler loading.

Ashori (2008) revealed that the most important criterion affecting the strength of wood composites is fibre size. Short-length fibres with the average size of 0.24–0.35 mm were proposed. These fibres demonstrated larger specific surface area, and the fibres distribution seemed to be more homogeneous in comparison with long fibre composites, thus promoted better fibres and polymer interfacial bonding. In addition, fibre swelling and breakage were minimally found.

Wood residues are currently gaining importance worldwide. This processed wood is either flours which have normally length to diameter ratio of 1/1 to 5/1 or fibres which have the ratio of slightly above 10/1. Wood flour can be considered as filler rather than fibres in composites (Rangaprasad 2003).

La Mantia and Morreale (2011) briefly noted some recent trends in natural fibre composites:

1. The development of 'green composites' with focus on making fully 'green' materials by having biodegradable polymers as matrices in place of synthetic polymers. Their findings are supported by other researchers (Netravali and

Chabba 2003; Lodha and Netravali 2002; Marsh 2003; Gould 2002; Nishino et al. 2003; Lee and Wang 2006; Bax and Müssig 2008; Huda et al. 2005; Plackett et al. 2003).

2. The problem concerning dispersion of fibres in matrices and polymer-fibre interfacial bonding (Scaffaro et al. 2009; Morreale et al. 2008a, b; Willett 1994; Coutinho et al. 1997; Nickel and Riedel 2003; Li et al. 2001).

3. The development of nanofillers as replacements for traditional micro fillers, thus to create 'green nanocomposites' field (Samir et al. 2005; Hubbe et al. 2008; Eichhorn et al. 2009).

Concerning the second issue, the problem in the manufacturing process should be considered as one of the worst problems, especially for producing products using natural fibre-reinforced thermoplastic composites. Researchers must have in-depth knowledge and the ability to predict some problems concerning the properties occurring during the manufacturing process (i.e. residual stresses, volumetric shrinkage and warpage distribution), especially when moulding thin-walled parts using the plastic injection-moulding process.

17.3 Challenges in Injection-Moulding Process for Wood Composites

In this section, issues related to challenges in injection-moulding process are discussed. They include thin-walled moulding process, minimizing the wall thickness and research on thin-walled parts.

17.3.1 Injection Moulding for Wood Composites

Injection moulding is a polymer and polymer composite manufacturing process in which injection-moulding compounds (in the form of granule) are injected into the mould through a hopper. Injection-moulding compound granules are fed into the mould via a heated barrel. Melting of the granules is caused by the heated barrel as well as the shearing action of the reciprocating screw inside the machine (Zainudin et al. 2001; Shaharuddin et al. 2006). Figures 17.1, 17.2, 17.3, 17.4, 17.5, 17.6, 17.7 and 17.8 portray the compounding process of injection-moulding compounds for wood fibre-reinforced thermoplastic composites. Figures 17.9, 17.10, 17.11 and 17.12 show machines, specimens and modelling used in injection-moulding process.

Research areas that are normally being focused in moulded part by natural filler-reinforced thermoplastic composites include processability and properties (residual stress properties, material warpage and material shrinkages) of injection-moulded thin-walled part.

Fig. 17.1 Virgin
polypropylene

Fig. 17.2 Wood powder

Fig. 17.3 Additives

Fig. 17.4 Drying and mixing processes

Fig. 17.5 Twin screw extruder

Fig. 17.6 Granulate carrier

Fig. 17.7 Front view of carrier

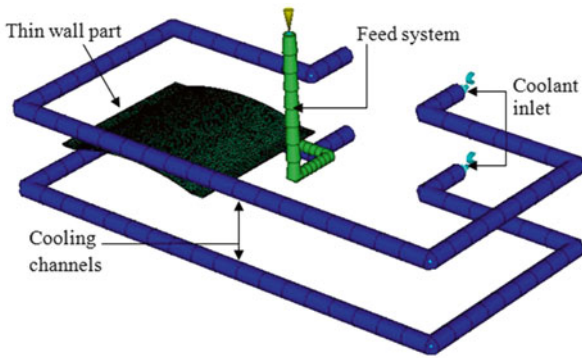**Fig. 17.8** Fine granulate crusher machine

Fig. 17.9 Typical injection-moulding machine

Fig. 17.10 Injection-moulding machine at INTROP, Universiti Putra Malaysia

Fig. 17.11 Justification of the optimum mould design (Moldflow simulation on thin-walled parts)

Fig. 17.12 Specimens of wood polymer composites

17.3.2   Thin-Walled Moulding Process

Nowadays, many thin applications use nominal wall thicknesses less than 1 mm compared to previous definition of thin-walled part (i.e. 1.5 mm) (Timothy 2001). However, Shoemaker (2006) stated that thin-walled materials are called 'advanced' for the thickness of 1.2–2 mm and 'leading edge' if the thickness is below 1.2 mm. He is of the opinion that the thin-walled definitions are considered on the basis of length to thickness ratio of the wall ranging from 100:1 to 150:1 or more. In addition, thin-walled moulding process also as known as when the part thickness smaller than 1.5 mm and (L:T) is greater than 100 (Chen et al. 2007). Sometimes, if the (L:T) is above 100 or 150 with thicknesses of 1 mm or thinner and a surface area of at least 50 cm^2, it is called ultra-thin-walled part and it was classified by Song et al. (2007).

17.3.3   Minimizing the Wall Thickness

Why do we want to reduce the wall thickness? The answer is 'cost'. Today, concern about economics and the environment causes the industries to focus on thin-moulding processes in their manufacturing. The specifications of a product can be made lighter, more compact and less expensive with sufficient mechanical properties and shorter moulding cycles (Anonymous 1995).

Therefore, manufacturers involving in research and development to produce 3C (computer, communication and consumer) products will be more concerned with product properties such as lightness, thinness, shortness and smallness (Shen et al. 2008).

According to Fischer (2003), decreasing the products' wall thickness means reducing plastic consumption and moulding with shorter moulding cycles. Hence, more than 70 % of the part's cost can be reduced. In addition, reducing the wall thickness also reduces the cooling time, which provides greater potential benefits, particularly when the cooling time is a significant portion of the cost in the moulding process.

Moving towards 'thin-walled technology', designers and manufacturers have increasingly explored the potential of thin-walled technology as a cost-reducing methodology that can reduce the moulding cycle time and material used (Slaviero et al. 2001). Preparing a smaller component enables the productivity rates to be increased, which reveals the manufacturer's attempt to rapidly compete in the world market (Rotheiser 2002).

17.3.4   Research on Thin-Walled Parts

Shen et al. (2008) stated that by looking at various injection-moulding conditions, the most appropriate number moulding gates during material filling can be determined. The geometry model analysed was a battery cover with a wall thickness on

four sides of 1.0 mm and a base central region of 0.2 mm. Ozcelik and Sonat (2009) carried out the way to optimize the strength and warpage of a consumer product (handphone cover) and the thickness being studied were 0.9 mm, 1 mm and 1.1 mm and the materials used were carbon fibre-reinforced polycarbonate ABS blend composites.

Tang et al. (2007) fabricated a mould for a thin-walled plate part with dimensions of 120 mm×50 mm×1 mm to study the optimization of the moulding parameters on warpage. Their research was performed to investigate the effect of injection-moulding parameters such as filling time, melt temperature and packing pressure and time on the warpage behaviour of thin-walled plate parts.

17.4 Formation of Residual Stresses in Injection-Moulding Process

Struik (1978) classified residual stresses into two categories: those induced by molecular orientation and those induced by rapid inhomogeneous cooling during solidification in the cooling stage. However, Williams (1981) divided residual stress in injection moulding into three major sources: two of these sources are similar to those presented by Struik (1978); in addition, Williams (1981) proposed residual stresses that were caused by the difference of crystallinity levels between skin and core layers.

Most researchers accepted that residual stress of injection moulding took place from the sources of residual flow stresses and residual thermal stresses (Baaijens 1991; Hastenberg et al. 1992; Kabanemi and Crochet 1992; Boitout et al. 1995; Liu 1996; Zoetelief et al. 1996; Chen et al. 2000; Gu et al. 2001; Lu and Khim 2001; Kamal et al. 2002; Lee et al. 2002a, b; Kim et al. 2005; Isayev et al. 2006; Park et al. 2006).

Residual stress is normally referred to as the stresses that remained in a moulded component and this took place when external loads were not present; only temperature or thermally induced loads and pressure or flow-induced loads existed. Thermally induced loads were caused by the moulding component that was not cooled homogenously (Wang and Young 2005) and the parameters associated with cooling like mould and matrix temperatures should be given proper attention. Flow-induced stress is normally lower than thermal stress (Zoetelief et al. 1996). In injection-moulding process, residual stress occurred either during moulding or demoulding of the component (Choi and Im 1999).

In the moulding process, residual stresses were distributed along the thickness of a component, and Kim et al. (2002) reported that on the surface and in the middle of the parts, the stress is in tension, while on other locations, the stress is in compression. Zhou et al. (2008) reported different findings, i.e. residual stresses were distributed equally across the part thickness. When the parts were being demoulded, warpage and part shrinkage were observed due to residual stress (Zhou and Li 2005a, b).

17.5 Formation of Shrinkage and Warpage in Injection-Moulding Process

Problems of accuracies in dimensions and related to mechanical properties and optical properties can be associated with the residual stress in a part (Michaeli and Potsch 1995; Hastenberg et al. 1992; Isayev and Crouthamel 1984; Zhang et al. 2002; Weng 2010). These common problems depend on the source of residual stresses, which are either thermally induced or flow induced. Normally, thermally induced residual stresses produced part warpage, environmentally related stress crack and part shrinkage (Isayev and Crouthamel 1984; Baaijens 1991; Powell and Housz 1998; Maxwell 2005).

Jacques (1982) reported that inhomogeneous cooling of a part may lead to stress uneven distributed in the part and in turn may lead to part warpage. This is particularly true when the wall is very thin. Cheng et al. (2009) suggested ways to minimize this problem by paying particular attention to shape of the part, innovation in cooling and moulding technologies. Similar solutions were proposed by Tang et al. (2007). Constant mould temperature during cooling is important (Chiang 2007). Cheng et al. (2009) suggested that in addition to temperature, packing pressure had the major concern to warpage. Studies are being conducted to determine which factors had the greatest effect in reducing warpage: packing time, mould temperature and filling pressure. Ozcelik and Sonat (2009) had carried out ways to reduce shrinkage and warpage in the plastic products that they developed. One way that they proposed is to use composite materials.

17.6 Optimization and Analysis of the Effect of Processing Parameters on Residual Stress, Shrinkage and Warpage

In research involving the injection-moulding process, most researchers employ certain statistical tools to optimize the variables for injection-moulding parameters such as temperature (resin, mould), time (packing, cooling, filling), and pressure (injection, packing) and to investigate the effect of the processing parameters on the quality of product. Giboz et al. (2007) reported that shrinkage and warpage normally depend upon injection-moulding processing parameters. They suggested ways to minimize warpage and shrinkage and they also suggested that attention should be paid to controlling injection-moulding parameters.

Researchers had used mould simulation package like (Moldflow and C-MOLD) as well as statistical tools to simulate the behaviour of composite materials during warpage and shrinkage. Examples of statistical tool used were Taguchi (including orthogonal array and S/N ratio), F-test and ANOVA methods. Among the findings includes the determination of the optimum process parameters affecting warpage of composite-walled composite products. Process parameters being considered include time, pressure and temperature.

Choi and Im (1999) studied the influence of injection-moulding conditions on residual stress formation inside moulded parts for use in accurate prediction against shrinkage and warpage. They observed that increases in the packing pressure and mould temperature resulted in more significant effects on the residual stresses. The increase was due to slow propagation of solid-liquid boundary when temperature of the injection mould was high. As the packing pressure increases, the difference of stresses (in tension and compression) becomes large, while the melt temperature and injection velocities have no effect on the residual stresses.

Sen and Bhattacharya (2000) showed that the distribution of residual stresses in starch/synthetic polymer blends consists of compressive stresses on the surface and tensile stresses in the middle of the part. The profile was affected by the injection and packing pressures, mould temperature, ageing and the amount of starch in the blend. However, packing time and melt temperature did not greatly affect the distribution of residual stresses. The magnitudes of both the compressive and tensile stresses across the thickness decrease with decreasing packing pressure. The rise in temperature of the mould and injection pressure had reduced tensile stresses. However, it did not significantly affect compressive stresses.

The formation of internal stresses depends on the results of cooling time diversification in moulded parts. Rapidly cooled and solidified surface layers create a stiff layer, which limits the shrinkage of a still-liquid core. The result of such a limitation is the existence of tensile stresses in the outside layer and compressive stresses in the inner areas. Rapidly increasing the pressure during the packing stages and an excessive clamping pressure cause packing of the particles; this results in high tensile stresses in the solidifying skin layers of the mould piece surface. As an adverse effect, the moulded part may be cracked when ejected from mould (Kansal et al. 2001; Arif and Fazal 2003).

Wang and Young (2005) studied the effect of the moulding condition on residual stresses of thin-walled parts. The mould temperature was observed to yield a significant distribution of residual stresses. There were different types of residual stresses at different melt temperatures. However, they observed that high-packing pressure range did not significantly affect residual stresses compared to low-packing pressure counterpart.

A review of past research showed that the study of moulded thin-walled parts made from natural fibre-reinforced thermoplastic composites in the injection-moulding process was not widely carried out. Research works have only concentrated on unreinforced thermoplastic and glass fibre-reinforced thermoplastic composites in making thin-walled parts during the investigation on the relations between the moulding parameters and part quality.

17.7 Potential Industrial Applications

Concerning industrial applications, several paths have been undertaken by worldwide researchers to expand and continuously improve the production of high-quality natural fibre composites (Davoodi et al. 2011). A mobile phone casing made of

polylactide (PLA) reinforced with kenaf fibres was launched by the NEC Corporation using a modified PLA developed by UNITIKA Ltd (Zini and Scandola 2011). The most suitable industrial applications of thin-walled parts focus on the electronics industry. The French moulding technology company RocTool has recently claimed that the thin-walled technology is going to expand and predicts increases in electronic applications. RocTool is the only company capable of producing electronic housing using engineering plastics with fibre contents that do not require painting; the thickness is 0.8 mm or less than 1 mm (Chris 2014a). The Taiwanese electronics industry moulder Ju Teng cooperated with RocTool to produce the latest smartphone and tablet casing component of less than 0.5 mm thick using glass- and carbon-reinforced thermoplastic composites. The Chinese mobile internet device and smartphone maker called Xiaomi is also exploring electronic packing applications with thin-walled casings produced for manufacturing its ultra-slim Mi2A device (Chris 2014b). Therefore, the best opportunities for lignocellulosic thermoplastic composites appear to be focused on electronic packaging. For how long will the idea of lignocellulosic thermoplastic composites be suitable for the thin-walled moulding process? In the initial stage, approaches using numerical simulations helped to identify the lignocellulosic thermoplastic composites that are suitable for thin-walled injection-moulding processes specifically for applications of similar casing parts. Based on these findings, this research became a platform for future exploration to expand the application of lignocellulosic thermoplastic composites in the development of thin-walled smartphone and tablet casings.

17.8   Conclusions

The development of wood-reinforced thermoplastic composites has been a hot topic recently due to the plan to reduce material costs and increasing environmental awareness. Specifically, wood flour-reinforced thermoplastic composites have a bright future for the aggressive exploration of new research scopes and applications. Wood fillers are also being used based on the reasons that were highlighted in the beginning of this review chapter. Therefore, the designer or engineer proposes the thin-walled part in their design, which is injection moulded using wood fibre-reinforced thermoplastic composites. However, in quality control of the part, the formation of residual stresses, shrinkage and warpage of the moulded part should be considered. This chapter provides a comprehensive review on previous research in material compounding, the properties of wood thermoplastic composites and the trend towards thin-moulding processing and the processability and properties (residual stresses, shrinkage and warpage) of injection-moulded thin-walled parts.

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