Injection molding WPC

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by

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Abstract

The use of wood-plastic composites, WPC, in commercial products is today limited. Current WPC products on the market are to a large extent limited to extruded products. There are strong reasons to increase the use of WPC. WPC can be manufactured from used plastic that otherwise cannot be recycled. This paper gives a brief description of the manufacturing of WPC, including wood filler treatment, the role of coupling agents and compounding. It describes the machinery used for producing WPC, and gives a introduction to mold manufacturing.

The use of WPC as an alternative to pure thermoplastics in injection molding processes is discussed. Furthermore it is described how WPCs differ from pure thermoplastics in terms of chemical and physical properties. The paper also describes the consequences of these properties in an injection molding cycle. The work finally puts focus on how to obtain process optimization through better understanding of pressure and temperature throughout the injection molding cycle.
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1. Introduction

1.1. Wood Plastic Composites

Composites are used in everything from toothbrushes to wind power towers and aircraft. They range from concrete to Kevlar fiber reinforced epoxy.

The composites in focus for this bachelor thesis are Wood-Plastic Composites (WPC). The advantages of WPC is that it can be made out of recycled plastic and sawdust or wood chips that otherwise would have been regarded as waste or fuel.

The WPC industry grew out of the desire to recycle polyethylene, PE, coming from applications such as grocery bags and milk containers, into useful products. (Yeh, Agarval and Gupta, 2009). The problem of recycling plastics is that the physical properties of polymers change to a very large extent depending on the impurities of the material. If the recycled plastic is instead used for the production of WPC, the effects of the impurities are minimized. WPC thus allows for the recycling of plastics in a larger extent than before, and with only seven percent of consumer plastics being recycled today (Waste Online, 2006), there is a great need for improvement.

The most common use so far is as a replacement for wood- in outdoor railings and decking. For these purposes the WPC is extruded profiles that resemble boards, poles or handlebars. Like all products manufactured through extrusion the freedom of design is limited compared to that of injection molded products. When used as a replacement for wood it has the advantages that it does not splinter or warp, it has a low maintenance and high dimensional stability. It also has good weather resistance and good UV-resistance. It also exhibits large freedom for design of shape and colour, (Haider & Eder 2010), at least compared to wood.

Although the WPC can be used for injection molding as a replacement to pure thermoplastics, there is a need to use this property to its full extent. While the market for extruded WPC products is growing with 10% per year (Haider & Eder 2010), the injection molded WPC products are marginal. There is an unexploited potential for development.

1.2. The use of WPC in injection molding

1.2.1. Chemical challenges

The use of WPC in injection molding phases a number of challenges. The first problem with WPC is to create strong bindings between hydrophilic wood and hydrophobic polymers. Therefore the binding between the wood and the polymers are improved through one or more coupling agents and/ or pretreatment of the wood. Because of these properties, the volume of the wood filler is moisture dependent. The volume of the plastic matrix on the other hand is temperature dependent. This causes internal shear stress and can cause cracks. Cracks are not only a problem in terms of decreasing mechanical properties, but the formation of cracks in the finished product also increase the wood surface exposed to moisture and the risk for rot and accelerated decay heightens. In order to come to terms with these problems coupling agents are used. The purpose of the coupling agents is to increase the binding force between the wood filler and the matrix. How this happens and is subject to debate (Klyosov, 2007). The coupling agent also decrease the hydrophilic properties of the wood filler. The hydrophilic properties of the wood filler can also be decreased by different treatments of the wood filler prior to compounding. This is crucial since wood plastic composites (WPCs)
made using unmodified wood material have been shown to lack in long-term
durability. (Segerholm 2007).

The physical properties are to a large extent set by type and amount of wood filler, matrix and
additives, but also affected by the extruder with which the compound is made. The process
by which the compound is made is referred to as compounding. Optimizing operation
settings of the pellet extruder has been shown to not only decrease the maximum moisture
absorption capacity of the WPC in question but also prolong the time it takes for the WPC to
reach maximum moisture absorption. A compound made with optimized extruder settings
during extrusion has been shown to have better moisture resistance that a compound made
with moisture resistance additives and the ideal settings on the pellet extruder. (Yeh & Gupta,
2008).

1.2.2. Recycling challenges

There are also a lot of challenges in terms of minimizing and handling the contamination of
the recycled plastic. One of the most interesting challenges is to handle any PVC put into the
recycled plastic because of PVCs ability to release chlorine gas which is highly volatile and
can lead to explosions in both the compounding extruder and the injection molding machine.
Since the purity of the recycled plastic available depends on local waste management systems,
there is in some cases the need to further clean and sort the plastic to improve the purity of the
recycled plastic.

1.3. Method

The methods used for this thesis is the study of empirical data. A series of experiments were
also started as a result of this project, but the results from those experiments will be
documented elsewhere.

1.4. Purpose

The purpose of this thesis is to describe the production of WPC, the process of injection
molding WPC as well as to establish in what way injection molding WPC differs from
injection molding pure thermoplastics.
2. Producing WPC

Wood fiber composites consist of plastic matrix and wood filler. In this chapter, the ways to manufacture WPC is discussed. As all fiber composites, the more ductile component is referred to as the matrix and the stiffer component is referred to as filler. It is often called fiber when it significantly improves the mechanical properties of the material and filler when the component simply is cheap and voluminous, creating structural stability rather than improving the strength of the material. Plastic and wood differs from each other in terms of chemical composition and this makes it difficult to bind them together. To create more and stronger bonds additives are added. Other additives are also added to decrease moisture absorption and increase the resistance to rot.

2.1. Producing wood filler

Producing the right wood filler is a very important part in making the WPC. It is preferable to use wood that is derived from recycled wood or sawdust or other residues of the forest industry. The reason for this is the decreased environmental impact and the low cost. This wood needs to be processed both mechanically and chemically. The mechanical processing serves the purpose of cutting the wood fiber to desirable size and shape. The chemical treatment serves to reduce moisture absorption and enhance the wood-plastic bindings. In short, the wood needs to be processed to ensure optimal specifications in the WPC. Regardless of the treatments the wood will be subjected to, it needs to be dried, since moisture will decrease the wood-plastic bindings and increase the risk of fungal attack and cause the material to rot.

2.1.1. Drying and cutting

The first step of optimizing the wood filler is to dry it. This is done in a vacuum oven. The temperature and time in the oven depends on type and size of the wood filler (Segerholm, 2007). The time and the temperature depends on the type of wood, the size and shape of the wood and the moisture content (for further reading see Goselin et al. 2003 and Segerholm, 2007).

The second step is to cut the wood into similar size and shape. The wood filler can be either in the shape of flakes, fibers, chips or flour and the size of the flour or fiber depends on desired characteristics of the finished product. There is an interval for feasible fiber length or chip size. If the filler elements are too small the binding force of the wood becomes so big that it cannot be compounded in a desirable way. If the filler elements on the other hand are big they result in decreased durability of the final product. In outdoor conditions, moisture absorption in the wood component combined with temperature induced movements of the polymer matrix cause deformations of WPC composites. (Segerholm, 2007) The moisture related change in volume increase with the size of the wood filler elements. This results in increased deformation and increased inner tensions in WPC with larger flakes or fibers. The greater tension in the WPC results in micro cracks and exposes the wood filler to oxygen and moisture and increases the overall surface area. This results in fungal attack and decreased tensile strength. Wood filler that is exposed to water over a long period of time suffers a loss in tensile strength. The decreased tensile strength is thus not only a consequence of the cracks but also from the increase in exposed filler and the decreased tensile strength of the exposed filler (Segerholm 2011). The size and shape of the chips or fibers also change during the
compounding (Segerholm 2007). This makes the desirable size dependent of the compounding extruder that will be used.

The fact that the wood filler changes shape during the compounding also raises the question of how much the wood filler changes in the injection molding process and if this change differs depending on the size and shape of the injection molded product.

2.1.2. Further treatments for wood fiber

Although the wood often can be put directly to compounding after it has been dried, it is preferable with some kind of additional treatment. The wood is treated in different ways to decrease the moisture absorption that is the result of the hydrophilic properties of the wood. This is very important since the moisture absorption results in warpage, fungal attack and decreased tensile strength. The hydrophilic properties of wood is a result of hydroxylic (OH) in the cellulose molecular structure. Treatments and additives can therefore be used to minimize the numbers of the hydroxilic groups. The treatments that are discussed here are acetylation, thermal modification and furfurylation.

- **Acetylation**
  The process of acetylation is a process whereby one hydroxilic group is replaced by one acetyl group. This is done by first impregnating the wood with acetic anhydride and secondly exposing the impregnated wood to a higher temperature in order for the reaction to occur (Segerholm 2007).

- **Thermal modification**
  Thermal modification is a method where the wood is subjected to a temperature of around 200°C for several hours in a low oxygen atmosphere (Segerholm 2007). Since this process does not require any additives it is the cheaper of the three.

- **Furfurylation**
  Furfurylation is a process similar to acetylation but where the wood is impregnated under pressure with furfuric alcohol. In contrast to acetylation it does not require any rise in temperature for the reactions to occur. The result of the process is that the furfuric alcohol polymerizes in the cell wall of the wood fiber, which results in a material with high dimensional stability due to its decreased tendency to absorb moisture. Furfurylated wood also exhibits improved mechanical properties and improved resistance to fungal attack (Segerholm 2007).

2.1. Making the matrix

The matrices in wood-plastic composites are thermoplastics. Because of the thermal sensitivity of wood the melt temperature of the plastic matrix needs to be below 200°C (Klyosov 2007) which greatly reduces the number of plastics suitable for WPC manufacturing. In North America in 2005, WPC manufacturers used 600 million tonnes of thermoplastics. (Klyosov).
2.2.1. Recycled plastic

The difficulty to recycle plastic was a major catalyst in the development of WPC. Owing to their ability to go from solid to liquid and back just by heat exposure thermoplastics can be reused numerous times. This implies that thermoplastics are also easy to recycle. Although good in theory the reality of waste management causes difficulties. In 2010, about 7% of the polypropylene that was consumed was recycled, and the remaining 93% went to land filling or energy recovery (Waste Online, 2010). The main problem in using recycled plastics is how to deal with the impurities of the recycled plastic and different polymers have a different sensitivity to these impurities.

The problem with the impurities is that they cause fluctuations in tensile and flexural modulus in such a way that these properties become impossible to estimate with sufficient accuracy. The advantage of WPC is that the wood filler minimizes the effect of these impurities.

The most used plastic in the world is polyethylene (Klyosov, 2007), which has led it to be the most commonly used matrix in wood-plastic composites. In 2005, 90% of the North American WPC was made using polyethylene as a matrix and the remaining 10% was mainly polypropylene, PVC and to a small extent ABS. In total about 35-40% of the plastic used in North American WPC is recycled and 60-65% is virgin plastic (Klyosov, 2007). Below are brief descriptions of the most commonly used matrices.

- **Polyethylene PE**

  Polyethylene is the most common plastic in consumer goods. There are various kinds of PE and they are classified based on their density because of the ease by which it is measured.

<table>
<thead>
<tr>
<th>Polyethylene</th>
<th>Density (g/cm^3)</th>
<th>Melt flow index (g/10 min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High density, HDPE</td>
<td>0.941-0.965</td>
<td>0.2-30</td>
</tr>
<tr>
<td>Medium density, PE</td>
<td>0.926-0.940</td>
<td>1-20</td>
</tr>
<tr>
<td>Low-density, LDPE</td>
<td>0.915-0.925</td>
<td>0.3-26</td>
</tr>
<tr>
<td>Linear low-density, LLDPE</td>
<td>0.915-0.925</td>
<td>0.1-100</td>
</tr>
<tr>
<td>Very low-density, VLDPE</td>
<td>0.870-0.914</td>
<td>0.02-10</td>
</tr>
</tbody>
</table>

  *Fig. 21. Polyethylene (Klyosov, 2007)*

  Polyethylene when used in WPC is mostly HDPE. There are also high molecular weight HDPE, HMW-HDPE, and ultra high molecular density HDPE, UHMW-HDPE. It is almost only HDPE that is because of the flexural weakness of LDPE.

  PE has a high resistance to wear and is resistant to weather. PE also has a strong resistance to chemicals in general, including strong acids such as sulphuric, nitric and hydrochloric (Klyosov, 2007) and high resistance to oxidation which minimizes the need for antioxidants for production and outdoor applications. PE also has a near zero moisture absorption which minimizes rot and fungal attack on the wood filler. These properties together make PE based WPC suitable for outdoor use. The major disadvantages of PE is its low tensile strength and its high thermal expansion-contraction, which is greater than that of wood. These properties create a need for extra
concern when designing products for outdoor use, both in terms of load bearing structures and the ways by which to design fasteners.

- **Polypropene, PP**

PP is next to PE one of the most widely used plastics in the world. Only in Europe the annual consumption of PP in 2010 was 9500 kilotonnes (Business Wire, 2010). This is not reflected in its use as a matrix for WPC, but could become more important in the future for products to be used indoors.

PP is lighter, stronger and stiffer than PE, but also more brittle. Although the annual production is as big as it is, the use of PP in WPC products is limited. This could be attributed to the relatively low weather resistance or the difficulties of fastening nails and screws in PP based WPC products. Since most of the WPC products are used for outdoor railing and decking (Klyosov, 2007) these is a crucial properties.

- **Acrylonitrile butadiene styrene, ABS**

ABS is used in computer screens and other home electronics, and the increasing amount of electronic waste effects can perhaps make ABS more attractive as a matrix for WPC in the future.

ABS has a low melt point of 100-110 °C but a high processing temperature 177-260 °C. ABS also has a high modulus and high resistance to compression. The main disadvantages of ABS is its high water absorption and its poor durability. Since most WPC produced today is intended for outdoor applications, these properties limits the current use of ABS.

ABS also has a low fire resistance. The high viscosity of hot melt leads to difficulties in processing. This results in torque up to 80% of maximum torque and, die pressure fluctuations and severe melt fracture at wood content above 50 wt. % and difficulties with pelletizing extruded strands (Klyosov, 2007).

The mechanical properties of acrylonitrile butadiene styrene, ABS, is noticably sensitive to impurities. If recycled ABS has more than 1 wt% of impurities, its mechanical properties are so unpredictable that the plastic no longer can be used in pure form (Yeh et al, 2009). However, if it is used in WPC, the effects of the impurities decrease dramatically. ABS containing 50 wt. % wood reinforcement remain essentially unchanged when the virgin ABS in the matrix is replaced by recovered ABS (Yeh et al, 2009).

- **Polyvinyl chloride, PVC**

Although very hard to recycle, there are some features that make PVC worth mentioning. PVC is to some extent used in WPC but it has a high density, so when used in WPC it is often foamed (Klysoy,2007).

PVC has a higher flexural modulus than PP and PE and like PE it has very low water absorption. Two features that make it suitable for WPC for outdoor use. The disadvantages of PVC is that it is relatively brittle in its pure form which makes PVC based WPC very brittle. It s flame retardant, but if it is not stabilized it releases HCl at temperatures above 70°C, which is a common temperature on outdoor surfaces.
dring warm summer days. PVC also has a very narrow processing window, it degrades fast at overheating which results in color change and odor which makes recycling of PVC generally unrealistic. A consequence of this is that a higher percentage of virgin plastic is used in PVC based WPC. PVC decomposes at 148°C which causes corrosion in the extruder and the injector due to the release of chlorine gas and creates the need for corrosion resistant metals and coatings (Klyosov, 2007). This is of great importance when it comes to recycled plastics since PVC when contaminating PE and PP can cause severe damage to the machinery since extruders designed for PE and PP are not built to withstand the kind of corrosion that occurs in processing PVC.

2.2. Making the compound

In order to blend the plastic and the wood together and make them bind to each other a process is necessary. This process is referred to as compounding and the finished WPC is referred to as the compound.

The compound is made with the help of an extruder, where the extruder often is of twin-screw type (Yeh et al, 2008). This means that there are two screws that are rotating and compounding the wood plastic mixture as it moves along the axis of the screws. The screw can be either counter rotating or rotate in the same direction and both have their different advantages (Yeh et al, 2007). There is a desire to have a high percentage of wood in the compound. However, high filler amounts result in high viscosity values that lead to processing difficulties, such as excessive extruder torque and the occurrence of melt fracture. (Yeh et al, 2008) This is normally avoided through the addition of additives. These additives differ depending on the type of polymers used.

2.3.2. Additives

As mentioned previously, the major challenge with producing WPC is to create strong enough bindings between the plastic matrix and the wood filler. This is done by coupling agents and a uniform distribution of the wood filler and the matrix. It has been shown that the amount and number of additives can be reduced through optimizing the settings of the compounding extruder (Yeh et al, 2008).

The most common additive is a coupling agent of some sort. The coupling agent is used to enhance and increase the bindings between the matrix and the wood filler or fiber.

The background theory is that the coupling agents need two functional domains. One domain that can form entanglements or segmental crystallization with the polymer and one that can form strong bonds with the filler through covalent bonds, ionic interactions and hydrogen bonds. There are mainly three types of coupling agents: Maleated polyolefins that bind with hydrogen bonds or ionic interactions, other bifunctional oligomers or polymers that bind with a ion-pair. How the coupling agents actually function is not fully known, but does not need to be viewed as important. What matters is the increase the flexural and tensile modulus of the material (Klyosov, 2007). What is very important is that the addition of coupling agents do not always improve either the tensile or the flexural modulus, it does however decrease the moisture absorption ability (Klyosov, 2007) which as mentioned before is important if the end product is intended for outdoor use.
The chemistry involved in the coupling of the cellulose and the polymers will not be elaborated further in this context (for further reading see Klyosov, 2007).

2.3.3. WPC – the end product

The end product of the compounding is WPC in the form of pellets, chips or flakes depending on weather the WPC will be used for injection molding or extrusion. It also depends on the brand and model of the injector or extruder.
3. Injection molding WPC

Injection molding is a process where a plastic or composite is injected into a mold under very high pressure. This is done with a injection molding machine that consists of two main parts, the injector and the clamping device. In order for the machine to operate it also requires a mold in where the product take form. The injector is where pellets, flakes or chips of compounded WPC are molten, pressurized and finally injected into the mold. The mold is then held together by the clamping device, enabling the correct pressure throughout the injection molding cycle.

Injection molding is suitable for making large series of a certain product. It has a high initial cost but allows for a high degree of automation and requires little maintenance. In terms of science, injection molding is rather complex. Injection molding belongs to the category of large scale system, involving many fields of science and engineering, such as rheology, heat transfer, fluid dynamics, friction, polymer science, and control theory. Optimal process parameters are difficult to achieve because the process is affected by a large number of interrelated factors that relate to the molding machine, molding material, and mold structure (Kim, Puk 2010). The many variables and the interdisciplinary nature of the knowledge required for injection molding also make it hard, if not impossible, to optimize the equipment and the procedures without extensive experiments.

Each type of plastic has its qualities and its boundaries for optimal performance. This has led to the use of molding process windows (MPWs). The molding process window is defined by the outer boundaries of system variables such as melt temperature, pressure and shear rate. The window for a specific part can vary significantly if changes are made in its design and the fabricating equipment used (Rosato et al, 2000). Below is an example of an MPW. To this is added not just the different parameters for optimizing the WPC itself but also the fact that the WPC changes depending on the process. Unlike pure thermoplastics, WPC is permanently changed during the injection molding process because of temperature and pressure related changes in the wood fibers (Segerholm 2007). Apart for this injection molding with a WPC is to a large extent similar to the injection molding of an ordinary thermoplastic and like ordinary plastic there is a need for an experimental approach for the machinery to be optimized for the application.

3.1. The injection molding cycle

The injection molding process consist of different stages. The first stage is the injection where 90-95% of the molten compound is injected into the mold. This is done under ambient pressure in the mold. The compound that is injected into the mold is referred to as a shot. The second stage is the packing stage. As the WPC plasticizes, it decreases in volume. In order to get the desired geometry additional WPC is supplied while the plastic from the original shot hardens. The third and final stage of the process is the ejection, where the injection molded product is pushed out of the mold with ejection pins. The size and thickness of the product that is to be manufactured determines the time each step takes, but to understand the process the following pictures have been included. What is interesting to notice is that the cooling accounts for the majority of the cycle time.

The change in temperature and pressure are fundamental in the process of injection molding. They are the two factors by which the process is controlled and altered.
Explanation to the figure

- **Fast closing**
  The first stage of the injection cycle is the closing of the mold. A crucial part of the cycle.

- **Fill**
  The second stage is the actual injection. In this stage the cavity in the mold is filled with plastic. During this phase 90-95% of the plastic is injected.

- **Pack**
  Once the filling of the mold is complete, more material is pressed into the mold. This is referred to as the packing phase and it is reflected in the graphs as increased pressure. The purpose of the packing is to build up that the pressure in the cavity so that no volumetric change occurs when the injected molded product cools off, there is only a decrease in pressure. The pressure during the packing phase depends on the type of plastic that is being used, as seen in fig 32-33.

Fig 31 Change in temperature and pressure during injection molding cycle. (Gutowski 2008)
• **Final cooling**
  The packing ends after certain period of time that depends on the plastic used, semicrystalline plastics like PE and PP require the pressure to be maintained longer than that of amorphous plastics such as ABS and PVC. After the gate freeze off the injection molded product cools off until it is solid enough to be ejected from the mold without unwanted change of form. The time of the gate freeze off is set so that the product has desired density after cooling and ejection. Since there is no additional pressure added during the final cooling the pressure drops. Time in the mould has a large effect on the residual stresses in the material. There are several different numerical models for estimations (Mlekusch, 1998).

• **Ejection**
  The ejection occurs when the injection molded product is stiff enough to be removed from the mold without permanent change of form, but when it is still so warm that it releases from the mold with ease.

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![Fig. 32. Cavity pressure in the injection cycle. Feed(1-3), Packing (3-5), Final cooling (5-6) (Kistler, 2011).](image)

**Fig. 32. Cavity pressure in the injection cycle. Feed(1-3), Packing (3-5), Final cooling (5-6) (Kistler, 2011).**

![Fig. 33. Cavity pressure for semicrystalline plastics such as PE and PP. (Kistler, 2011).](image)

**Fig. 33. Cavity pressure for semicrystalline plastics such as PE and PP. (Kistler, 2011).**

![Fig. 34. Cavity pressure for amorphous plastics such as PVC and ABS. (Kistler, 2011)](image)

**Fig. 34. Cavity pressure for amorphous plastics such as PVC and ABS. (Kistler, 2011)**
Following formula shows the cooling time as a function of wall thickness in the injected product.

\[ t_{cool} = \frac{(\text{thickness}/2)^2}{\alpha} \]

Where \( \alpha = 10 \text{ sec for polymers. (Gutowski). This value is different for WPCs since they do not have the same thermal conductivity as pure polymers and the stiffness is different. The reason to the lower cooling time is the wood filler. The material hardens faster since only the matrix needs to cool. The fact that the molded part starts to cool down and solidify near the cavity wall inhibits the pressure transfer (Kistler, 2011).}

### 3.2 Machinery

![Injection Molding Machine](Image)

*Injection moulding machine (Wikipedia, 2011)*

#### 3.2.1 The Injector

The injector is where the first stage of the injection molding process takes place. The injector is the part of the machine into which plastic or in the case of WPC pelletized compound is fed, molten, and then injected into the mold. The machine is often built to meet specifications of a certain product. There is no universal injection machine but the basic functionality is the same.

The pellets are fed into a container that then distributes the pellets to a screw. This screw is surrounded by heat generators and it is the heaters that together with the screw melt the WPC. As the screw rotates it also transports the molten WPC from the hopper towards the nozzle. The primary purpose of using a screw located in the plasticizer barrel is to make use of its mixing action (Rosato et al 2000).

As the plastic is transported further towards the nozzle, the volume decrease as the diameter of the screw core increase, thus increasing the pressure. The screw has three sections, for feed, melting and metering. (Rosato et. al 2000). The screw’s compression ratio can be determined by deviding the flight depth in the feed section by that in the metering section. Depending on the plastic processed ratios usually range from zero to four. (Rosato et al 2000). The ideal compression ratio of WPC is lower because of the risk for moisture explosions to occur. Different manufacturers of injection molding machines have different designs on their screws.
and the designs are very often patented. For further reading on screw design and patent numbers on these see Rosato et al., 2000.

### 3.2.2 The Clamping device

When the molten plastic is injected into the mold the mold needs to be held together in order for the pressure to be maintained. This is done by the clamping device. The clamping device opens in the end of the cycle and ejects the finished product. The mechanism by which the clamping device maintains this pressure can be designed in a number of ways. The most widespread solution is to use a locking knee joint that is operated through a hydraulic cylinder.

The two opposing plates that accommodate the mold is referred to as platens. The platen closest to the injector is fixed, while the opposing platen moves back and forth on rails in order for the different parts of the mold to separate and the finished product to be ejected.

Inadequate pressure on the mold from the clamping device results in flashing, the mold halves are pushed apart by the pressure and the

The volume of the molded product is determined by the shot volume of the injector. The required force of the clamping device on the other hand is determined by the area projected on the mold by the product. This is the size of the area where the pressure from the injection is pressing on the movable platen of the clamping device. The force that the clamping device can be subjected to is often reflected in the model name of the injection molding machine. The force can range from 30 kN up to 8000kN (Rosato et al.).

![Fig 36, area of projection](http://mould-technology.blogspot.com/2008/10/how-to-calculate-clamping-force.html)
3.2.3 The mold

The mold consists of at least two separable parts that together form the cavity in which the WPC is injected to form a product. Due to the behavior of the plastic or composite injected into the mold there are many different criteria that needs to be met in order for the injection molding to operate smoothly and for the final product to behave according to specifications. In order to maintain pressure in the melt, wall thickness should be constant where possible. The pressure is as mentioned previously which calls for the avoidance sharp corners in general, since these result in uneven pressure. A key factor to minimize unwanted and unequal shrinkage and gradual changes in the wall thickness causes gradual changes in temperature and results in warpage.

Since the plastic shrinks when it cools down, the core and the cavity of the mold are angled to ensure that the molded part is easily ejected from the mold. This angle is referred to as the release angle.

Basic features of an injection mold

- **Sprue:** A sprue is a channel through which to transfer molten WPC from the injector nozzle into the mold. The sprue needs to be wider than the runners.

- **Runner:** A runner is a channel that guides molten WPC into the cavity of a mold. Often with a profile in the shape of a semi-circle. The circle is the optimal profile to keep the melt fluid as long as possible with a minimum of melt but the semi-circle is often applied because it only involves operations on one half of the mold. They can be hot or cold depending on the type of product to be molded. They can also be designed with valves to increase the control of the fill. Equal length or valves.

- **Gate:** A gate is an entrance through which molten plastics enters the cavity. More narrow than the runners to ease the release between the product and the sprue. Different types of gates: Side gate, fan gate, double side gate, ring gate, diaphragm gate and sprue gate.

- **Ejector pins:** In order to eject the molded product from the mold, ejector pins are used. Ejector pins are pins attached to the moving platen and are integrated in the mold design. They are protracted with a hydraulic piston. They are often designed with tolerances that allow for the air inside the mold to be released during the filling phase.

- **Undercuts:** The products are often more advanced that what a two part mold allows and in these cases molds with multiple parts are used. The mold can also have a multitude of inserts. These can be used either for manufacturing different versions of the product with the same mold or to create undercuts. Undercuts are holes and cavities in a direction that is not in line with the direction in which the mold opens that are impossible to include in the mold otherwise. In order to split a mod with undercuts, the undercuts are removed from the mold before the mold opens and the final product ejected.
3.2.3.1 Materials in the mold

The main reason for the high cost of the molds is related to the large series that are produced. It is not uncommon for a mold to be used for a million cycles. In order to withstand that kind of environment and keep the tolerances within proper boundaries, the demands on the material is very high. Materials used for molds can be divided into ferrous metals, nonferrous metals and non metallic materials.

Ferrous metals, steels, are the most commonly used materials. There are a number of reasons for steel to be the primary material for mold making. Steels permit economical machining and they have a capacity for heat treatment without problems. They also have sufficient toughness and strength, are easy to polish and resistant to heat and wear. In addition to this they also have a high thermal conductivity and are resistant to corrosion (Menges et al. 1993). Steels have higher costs but are preferred because of their durability. The steels used for injection moulds are case hardening steels, nitriding steels, through-hardening steels, tempered steels martensinic-hardening steels, corrosion resistant steels, refined steels. Of these, the most common is case-hardened steel. The reason for this is that cementite is formed during successive hardening, which gives the mold a hard and wear resistant surface, and at the same time a ductile, shock resistant core (Menges et al. 1993). For complex geometries or very large series, martensic materials are often used because of its very high hardness and high toughness. (Menges et al. 1993).

During the design phase it is preferable to make test molds that are easier to machine than steel. Since the test molds do not need to produce large series a softer material can be chosen to ease the machining and cut developing time and cost. A suitable material in this case is aluminium which is easy to machine and enable molds that can be used up to 1000 cycles, which is enough for test series.

3.2.3.3 Processing of the mold material / producing the mold

Because the mold material needs to be durable the production of the molds is costly and time consuming. The means by which the mold is produced varies and depend to a large extent on the material. The ways of manufacturing molds can be divided into the methods that involve material removal and those that do not.

Methods without material removal
Casting is historically the most common way to produce molds. The greatest advantage of casted molds is the minimized material loss that in cutting operations can be as high as 30-
The most commonly occurring casting methods are sand casting, ceramic casting, and die casting.

Sand casting is primarily used for producing large molds up to 3 tons per mold half (Menges et al. 1986). The major disadvantage with sand casting is that it requires additional machining. If there are high demands on surface reproduction, ceramic casting is done instead.

Ceramic casting is done in many steps, starting with positive pattern in wood plaster, plastics or metal. The negative of this is then created using silicone rubber and this in return is used to produce a ceramic positive. The formula for the ceramics depend on the requirements. This ceramic positive is then finally used to produce the metal negative that is the mold (Menges et al. 1986).

Die casting is the procedure of casting the metal that is later to become a mold in another mold of metal. The metal is subjected to pressure until it is solid which creates very good tolerances and a minimum of anomalies in the material (Menges et. al 1993). This process is very expensive because of the machinery that is required. It is for big production series where it is preferable due to the possibility to create new identical molds fast and with high precision. Because of the advances in material technology the number of products that can be produced with a single mold increasing. This together with the ever shortening time that a product is attractive on the market makes die casting obsolete for many appliances. However, when it comes to injection molding products with high wear like glass fiber reinforced plastics die casting is the only sound alternative for large scale production. The materials suitable for casting are basically all types of ferrous metals and most types of non-ferrous metals.

Metal spraying is another mold making technique suitable for prototyping. Metal spraying provides a highly accurate surface reproduction and permits prototyping or molding of small series under conditions close to production level (Menges et al, 1993).

There are several other ways to manufacture molds without material removal. Electrolytic disposition is a method where a thin layer of hard material is deposited on a pattern. This is done by immersing the pattern in an electrolyte, a aqueous solution of metal salt where the metal salt is the intended coating material. The pattern is then connected to the positively charged anode and negative anodes are also submerged in the electrolyte. When a DC source is switched on, the salt will be deposited on the pattern (Menges et al, 1993).

Another method that does not involve the removal of material is hobbing. When hobbing a mold, the hob is a hardened and polished version of the product that is intended to be injection molded. The hob is forced into a blank of steel at a speed of between 0.1-10 mm/min. It is a method that does not allow for very large products because of the limited pressure that can be tolerated without deforming the hob. The maximum pressure is ca. 3000 MPa but ideal conditions are around 300 MPa (Menges et al, 1993).

Material removing operations
The methods that involve material removal vary to a great extent depending on the mold and on the specifics of the mold (Menges et al, 1993).
Machining is the most known of the material removing operations. It is forming by cutting operations. It is the most common way there is to reshape an object. It is also the most widely
employed method to of mold fabrication (Rosato et al, 2000). This is likely the result of better CNC machines and especially the development of CAD/CAM tools and software. For the manufacturing of molds, machining is mostly used for processing softer materials, like aluminium and certain types of steel. The softer the material, the more freedom there is regarding choice of tools, RPM and cutting speed. It also goes a lot faster with softer materials which makes this kind of mold ideal for prototyping.

Machined parts often require additional surface treatment to meet specifications. There are various types of surface treatment ranging from grinding to highly sophisticated methods. Grinding and polishing is best described as cutting with a cutting with a large number of undefined cutting edges.

There are a number of limiting factors in terms of possible machining operations. The radius of the cutting tool limits the depth of the operation. If it is too deep, the tool bends and it results in poor surface quality and vibrations and in worst cases fracture of the load.

Other surface treatment methods are vibratory finishing, sand blasting, pressure lapping, electrochemical polishing and electric discharge polishing. (Menges et al, 1993).

Other material removing operations are the Electric Discharge Forming processes (EDMs). The combination of its ability to create complex geometries and its ability to process annealed, tempered and hardened steel make electrical discharging a very good method for mold manufacture. (Menges et al, 1993).

Electric Discharge Machining (EDM), cutting by spark Electrochemical Machining (ECM), Chemical Material Removal - Etching.

Menges et al. (1993) also mention cutting by spark erosion with travelling wire electrodes. This type of spark erosion is capable of the same operations as a saw. The difference is that spark erosion can be used to process larger molds and stronger materials than what is possible with a saw. The downside of the technology is that the operations are time- and energy consuming.

3.2.3.4. Designing the mold

The mold can be created in the following steps. This methodology is the one that was during the experiments that were started during the writing of this paper.

High costs of making the moulds and low possibility of making alterations to the moulds after manufacture creates a need for a mould developing process that incorporates experiments and prototyping. It is advisable to make at least one prototype in a softer metal before manufacturing the final mold. The prototype is less costly because it is made of a cheaper material that requires less machine time which also cuts down the production time of the mold to a great extent.

1. **CAD of the product**: An accurate model of the product intended for production is crucial for designing a mold.
2. **Injection molding simulation of the product**: Simulations of the molding are done to minimize internal stress in the molded product. The internal stresses are minimized
through the size, shape and position of the runners. At this stage it is also determined if additional cooling or heating is necessary in the cycle.

3. **CAD of the mold:** When the runners are set the mold can be modeled. The complexity of the mold depend on the number and complexity of the cavities in the mold. Concern has to be put on the manufacturability of the mold.

4. **CAM of the mold:** Once the mold design is finished, the process of manufacturing it starts. The CAM will be done in at least two versions. The first CAM file is for the prototype made in a softer metal and requires less machine time and allows for the mold to be machined.

5. **Prototype mold fabrication:** When the CAM is finished and tested, the prototype mold is manufactured.

6. **Test run:** When the prototype mold is manufactured a test run is conducted to see if the design of the mold is good or if changes are necessary. If changes are necessary the CAD of the mold needs to be remade.

7. **CAM of the final mold:** Once the test run is conducted with satisfactory results, the final design is reached and the preparations to manufacture the final mold can start. Since the final mold is made from a harder material different parameters are required during the manufacturing. If the final mold allow for machining as the prototype the rotation feed and the tools need to be changed. In most cases a different manufacturing method is necessary. A common method for production is electrolytic disposition for two reasons, it can process most materials and it allows for a great deal of design freedom.

The following formula can be used to make estimate the machining time of the mold.

\[
c_m = \sum_{i=1}^{n_M} \cdot f_{mi} \cdot a_i
\]

where

\[
\sum_{i=1}^{n_M} a_i = 1
\]
$c_m$ is time factor for the specific machining procedure, $f_{m_i}$ is the Machining factor, $a_i$ is the percentage of the respective machining procedures and $n_M$ is the number of machining procedures (Menges et al. 1993).

3.3. Effects of fibers / using WPC

The major difference between injection molding WPC and injection molding a pure thermoplastic is that the thermoplastic can go from solid to liquid and back without changes in the chemical composition while the heat and the pressure in the injector and when the plastic is injected causes permanent change in the volume and the properties of the wood filler (Segerholm 2007).

3.3.1. Shrinkage

As mentioned in 3.1. the pressure and temperature in the mold and the compound differs depending on what kind of plastic is injection molded. When injection molding WPC the pressure is different throughout the cycle. Because of friction there can be a higher pressure during the filling of the mold because of greater internal friction in WPC with high wood content. At what percentage this occurs should depend on type and size of the wood filler together as well as the type of matrix. The temperature dependent volume of the matrix and the constant volume of the wood filler give less shrinkage in WPC than in the matrix pure form (Segerholm, 2011). This means that a lower pressure is needed during the packing phase of the injection cycle (section 3.1) when using a WPC compared to when using the matrix of the same WPC in pure form (Gosselin et al., 2006). It also means that the release angles can be lesser when using WPC than when using the matrix in its pure form.

3.3.2. Effects of fiber length

**Microcracks**

If the fibers are too long the stresses in the injection molded product when cooling will result in microcracks. This is because the matrix shrinks more than the filler. When the fibers are too long, the volumetric change in the matrix causes stress in the material that is greater than the binding force between the matrix and the filler. Microcracks can also occur because of too long fibres if the injection molded product is intended for outdoor use or other in other ways exposed to moisture. If the fibers are too long the moisture dependent volume change of the wood filler will result in cracks in the material since the moisture dependent change in volume increases with chip size (Segerholm 2011). This is the most crucial consequence of mixing plastic and wood, a material with a temperature dependent volume a material that has a moisture dependent volume.

**Anisotropic properties**

Another result of the fibers is that WPC in contrast to thermoplastics exhibits anisotropic behavior, the tensile strength differs depending on from what direction the outer force is applied. This shows that the fibers are not randomly distributed but tend to align with each other in during the injection molding (Segerholm, 2011). This is also visible in injection molded WPC products.
All injection molded products show a weaker structure where two meltfronts meet and form a weldline. This structural weakness increases in products made from WPC due to the different fiber directions in the different meltfronts. When it comes to consumer products they can also have a big effect on the visual impression of the product since the weld lines become more visible. One can assume that an alignment of the fibers occur in the extruder as well, but since the WPC is pelletized after compounding it should not have an effect on the injection molded product.

If the fibers are too small the total area of the chips is very large. The result of this is that the binding forces between the chips and the plastic as well as between the chips and the screws of the compounding extruder are so great that it makes the compounding impossible (Segerholm 2011). The injector requires too much torque. The fiber directions of WPC, the anisotropic properties, are created in the injector (Segerholm 2011) and it is reasonable to assume that an alignment also occurs during the compounding, but because of the pelletization the anisotropy of the extruder is not necessarily noticeable in the injector. What would be interesting to look into is how and if the operation settings of the extruder and the size of the pellets affect the anisotropy of the injection molded product.

3.3.3. Moisture

Another effect of WPC is the occurrence of vapor explosions. Moisture trapped in the wood filler is released during both the compounding and the injection. If the moisture content is high it can result in the instantaneous formation of a large amount of vapor, a vapor explosion. The pressure impulse from the vapor explosion can cause great damage to the screw, in some cases accelerated wear, and in some cases instant breakage.
4. Need for further research

The parallel development of WPC and the machinery is not feasible since it would result in very high cost. The first step of appropriate procedure would be to optimize the plastic to meet the specifications of the final product. The second step is then to match the machinery to achieve optimal manufacturing conditions. There is a need for further research both on the behavior of different types of WPC when injection molded and on the recyclability of different WPCs. Through this thesis three important questions were identified and experiments were designed to answer these questions.

4.1 Optimizing existing WPC for injection molding

Since most WPC at present is used and developed for extrusion there is a need to understand how operation parameters and product geometry affect the performance of different types of WPC. The following questions need to be answered.

1. **Determining optimal pressure throughout the cycle.** Since the temperature dependent shrinkage of a WPC is less that of the matrix in its pure form, the optimal pressure needs to be determined for individual WPCs to achieve optimal performance.

2. **Determining the optimal temperature throughout the cycle.** Although $t_{\text{max}}$ is similar in extrusion and injection molding, the time during which the WPC is exposed to these temperatures differ.

3. **What is the tensile and flexural modulus of a certain WPC when injection molded at optimal pressure and temperature?** This is needed since the pressure and the temperature has permanent effect on WPC. Since WPC is anisotropic these properties need to be tested at different fiber directions.

4. **Does the geometry of the molded product affect the tensile and flexural modulus of the WPC?** Since WPC is anisotropic the geometry of the product does have an effect and the significance of this effect needs to be established.

5. **How does recycling affect the modulus of WPC?** This is very relevant because of the pressure and temperature related permanent change of the wood fillers that occur in the injector (Segerholm, 2007).

Multiple series of experiments can be conducted to answer all above questions. Below are suggestions to how they can be conducted.

**A. Tensile test bars at different pressure and temperature**

An interesting series of experiments for determining optimal pressure and temperature as well as determining tensile modulus and flexible modulus as well as anisotropic properties would be the following:

- Multiple tests with injection molded tensile test bars.
Suitable variables are pressure and temperature. The pressure during the filling of the mold can be calculated from the torque of the injector and the cavity pressure can be measured by sensors mounted in the mold.

This experiment answers questions number 1, 2 and 3. It gives the optimal pressure and temperature as well as the tensile strength and modulus at optimal operation. Fiber direction can also be included in the parameters with 0, 45 and 90° fiber direction. Since this triples the number of tests, this should only be done if there is reason to believe that the maximum modulus in the different angles to the fibers of the tested WPC occurs at different pressure and temperature.

**B. Does geometry affect tensile and flexural modulus?**
The following tests can be conducted to determine if the modulus is affected by geometry.

- Multiple tests with tensile test bars cut out from an injection molded block with 0, 45 and 90° fiber direction to determine any difference.

Although unlikely, if such a distance does exists there is a need to develop a set of experiments to determine the maximum span of properties or even test individual products.

**C. How does recycling affect the mechanical properties of WPC?**
Another interesting experiment would be to examine the recyclability of different WPC. This could be done by:

- Injection molding a proper amount of tensile test bars from pellets with a known size and test their properties with varying fiber directions, for example 0, 45 and 90°

- Pelletize the used tensile test bars and injection mold new tensile test bars and test their properties for any noticeable change in the properties.

To avoid any weakness caused by the testing of the material as well as to determine to what extent load bearing affect the recyclability of the WPC there should also be a statically satisfying amount of tensile test bars injection molded from the same batch of WPC that is not subjected to tests but just pelletized to be injection molded again.
5. Conclusion

The reason that WPC is not so commonly used for injection molding could perhaps be attributed to the lack of research on how the material changes over time but it could also be the result of product designers lack of understanding for the material. Because of its wood content WPC is primarily used as a replacement to wood, and the lack of knowledge in design departments could explain the large and fast expanding market for extruded WPC product and the almost non-existent market for consumer products made from WPC.
References


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