Manufacturability of Wood Plastic Composite Sheets on the Basis of the Post-Processing Cooling Curve

Sami Matthews,[a,]* Amir E. Toghyani,[a] Harri Eskelinen,[a] Timo Kärki,[b] and Juha Varis [a]

Extruded wood-plastic composites (WPCs) are increasingly regarded as promising materials for future manufacturing industries. It is necessary to select and tune the post-processing methods to be able to utilize these materials fully. In this development, temperature-related material properties and the cooling rate are important indicators. This paper presents the results of natural cooling in a factory environment fit into a cooling curve function with temperature zones for forming, cutting, and packaging overlaid using a WPC material. This information is then used in the evaluation of manufacturability and productivity in terms of cost effectiveness and technical quality by comparing the curve to actual production time data derived from a prototype post-process forming line. Based on this information, speed limits for extrusion are presented. This paper also briefly analyzes techniques for controlling material cooling to counter the heat loss before post-processing.

Keywords: Cooling rate; WPC post-processing; Forming; Cutting

Contact information: a: Lappeenranta University of Technology, Laboratory of Manufacturing Engineering, Skinnarilankatu 53850, Lappeenranta, Finland; b: Lappeenranta University of Technology, Laboratory of Composite Materials, Skinnarilankatu 53850, Lappeenranta, Finland;
** Corresponding author: sami.matthews@lut.fi*

INTRODUCTION

Extruded wood-plastic composite (WPC) sheets are one type of WPC semi-products that have gained industrial interest because of their good environmental impact, together with their reasonable mechanical properties. WPC as a term covers a wide range of composite materials made from different plant fibers using thermosets or thermoplastics as the bonding matrix. WPCs have become a well-studied development in recent years because of the environmental restrictions set on purely polymer-based materials. This is advantageous for WPCs, as it is now possible to use recycled fiber sources and find new uses for waste otherwise going to landfills. In comparison to wood, Klyosov *et al.* (2007) lists lower maintenance requirements, including no need for staining, sealing, and painting; higher resistance to termites and microbes; the absence of knots and splinters; and environmentally friendly characteristics.

This paper is part of a bigger research project investigating the post-processing of WPCs. Post-manufacturing means material processing after material fabrication by extrusion. This development involves three integrated viewpoints: material, quality, and process, which all influence the end success of the production. Ignoring one area would cause the other areas to fail in the technical or economical aspect. In general, there are two ways to improve the manufacturing stage: optimizing the product and optimizing the manufacturing process. In addition, the development of the manufacturing process is often based on an evaluation of economic and technical aspects. The economic aspects are directly related to the length of the manufacturing stages, which in this case are directly linked to temperature changes and cooling. The longer the product takes to cool, the more space and time is required. On the other hand, if the cooling is too rapid, the temperature will fall below the formable area prematurely and the quality of the formed product will suffer. On the basis of this information, it is important to be able to control the material temperature during this process. In technical aspects, cooling is relevant for the manufacturing stages that demand tight tolerances, such as cutting and forming; therefore, these two manufacturing methods are used as references in evaluating the effects of the material cooling rate. Having the material at the optimal temperature makes it possible to achieve higher productivity and product quality. The aim of this paper is to verify the operation of the post-process production line of an unheated wood plastic composite in terms of material temperature during the post-process stage.

The material investigations are based on actual cooling experiments in a factory-like environment, as the primary aim is not to check the material properties in isolated space, but to check the material behavior in a real production environment. In this study, an example material labelled simply as the composite material is used. This material was selected because it has good formability characteristics and is similar to the commercial materials used in the WPC industry.

Sonmez and Eyol (2002) have studied the optimal post-manufacturing cooling paths for thermoplastic composites. Their purpose was to determine the optimal cooling scheme to minimize the processing time during the cooling stage in press molding. They noticed that optimal cooling could be analyzed by utilizing heat transfer analysis and the temperature profiles through the thickness of the composite plate and that the heat transfer analysis was mostly connected to the temperature-related material properties of the polymer used in the composite. However, as Sonmez and Eyol focused on reducing the processing time in molding, the viewpoint concerning specific manufacturing stages was not included in their optimization model. This paper considers the special aspects related to optimizing the forming and cutting stages.

Previous research has shown that WPCs as polymer-based materials are greatly dependent on the material temperature and the matrix polymer type and that the performance of high-density polyethylene (HDPE) and HDPE-based composites is strongly dependent on the processing time and temperature of manufacturing (Yang *et al.* 2013). It is said that the cooling rate of polymers is low because of their poor thermal conductivity (Tan *et al.* 2012). The thermal expansion of WPCs under elevated temperatures is a well-known phenomenon, and according to Yang *et al.* (2013), the linear coefficients of thermal expansion-contraction for wood are significantly lower than those of plastics and WPCs. The values for wood are independent of temperatures between -51 and 130 °C. Because HDPE is a continuous phase in WPCs, linear expansion and contraction are related to polymer molecules. When treated at elevated temperatures, polymer molecules begin to move and steadily reach their thermodynamically settled state, resulting in composite expansion. This, in addition to absorption of water, is another reason for WPC products to expand. In addition, shrinkage of WPCs has an important effect during post-processing. Shrinkage happens when a plastic-based board, extruded and pulled from the die, cools too fast. Too fast means that the stretched long polymer molecules coming from the die do not have enough time to return to their thermodynamically favorable coiled form (Klyosov 2007).

Sonmez and Eyol (2002) have presented also another relevant viewpoint, which is similar or at least analogic with the WPC studied in this paper. They have noticed that residual stresses can have a significant detrimental effect on the performance of composite structures by causing defects, *e.g.*, void formation during solidification, reducing strength, and initiating cracks. They underline that the residual thermal stresses should be within tolerable limits to ensure reliability during the use of the product. The tentative observations with the tested WPC showed that under impact forming, the fully cooled product seemed too brittle. According to Wijskamp (2005), who has studied the processing of thermoplastic composites, depending on the initial process temperature, the composite sheet can experience a thermal shock as soon as it is pressed between the pressing tools, as it is rapidly cooled from the outside inwards. The phase formations of polymers in the composite depend on the cooling rate. According to Wijskamp, the selected cooling rate during the thermoplastic composite processing can affect both the shrinkage of the material and its mechanical properties.

Brucato *et al.* (2002) state that investigating polymer solidification under processing conditions has become a necessary step to predict the final polymer properties. As solidification in industrial processes often involves flow fields, high thermal gradients, and high pressures, the development of a model able to describe polymer behavior turns out to be really complex. The same situation was met with the WPC process studied in this paper. Another analogical aspect can be found in the injection molding of polymers. According to Liu and Gehde (2015), heat transfer is one of the most important segments in injection molding because it significantly affects the temperature distribution of the component and alters the temperature distribution in the mold, thereby affecting the mechanical behavior and dimensional precision of the plastic component, as well as production efficiency. In our case, the question is not of the first molding stage, but the same phenomena are present during the post-processing stage, in which the WPC plate is at an elevated temperature and is pressed into its final geometry.

The temperature-related phenomena highlighted in previous studies (Sonmez and Eyol 2002; Wijskamp 2005; Tan *et al.* 2012; Yang *et al.* 2013) needs to be taken into account when designing a successful manufacturing process for extruded WPCs, indicating the importance of monitoring the temperature and controlling the cooling in the development of manufacturability.

EXPERIMENTAL

In this paper, the cooling rates of WPC sheets with 3 mm thickness with a composition of 44% wood fiber, 50% polyethylene (PE), 3% coupling agent, and 3% lubricant are investigated, as the sheet geometry and the material properties offer promising possibilities for multiple post-production techniques; as a polymer-based material, WPCs have the potential problem of premature cooling at room temperature during post-processing. To measure the cooling rate, the specimens were located in a laboratory space at 21 °C. This location represents a typical factory space. In this kind of uninsulated open system, the WPC can transfer heat to the surroundings by conduction, heat gradient-induced convection, or radiation of heat. Conduction was prevented, but heat gradient-induced convection and radiation were unrestrained, similar to a real production environment. In a typical industry setting, the material is often conveyed over metal rollers, which conduct heat. This heat loss was simulated by having a metal grille under the specimens, as shown in Fig. 1.

Because an online extruder could not be used during the study, prefabricated WPC sheets were used. To simulate the post-process, the sheet was placed in an electrical oven at 150 °C (+-3 °C) for 15 min. The temperature was measured using a National Instruments USB-TC01 transducer and included J-type exposed thermocouple. The measurements started 10 s after the sample was taken out of the oven. The temperature was measured at the center and 10 mm from the edge of the specimen. The size of the specimen was 300 mm^2 with 3 mm thickness, as shown in Fig. 1.

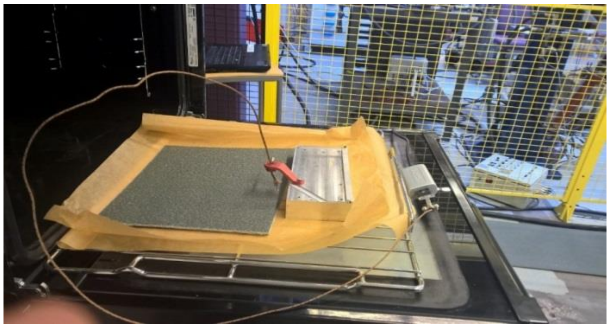

Fig. 1. Heat sensor attached and temperature measured from the edge of a WPC sheet

The detailed analysis of the measured cooling rate curves made it possible to use mathematical tools to estimate the best curve fitting to describe the behavior of the material. Further on, it will be possible to find the critical time and temperature values to show the areas in which the forming and cutting process should be made. The curve fittings can be made either for the whole set of measured values or stepwise to strengthen the importance of the time period when the cooling starts. The curves were fit using the curve fitting toolbox version 3.3.1 in MathWorks MATLAB 2013a.

Although fibers, coupling agents, and lubricant play a large part in the material properties of WPCs, the overall material properties are not dramatically changed by these ingredients at different temperatures (Klyosov 2007), and they were therefore not investigated in this study. For example Stokke *et al.* (2014) stated that dry wood fibers in WPCs endure thermal degradation only at temperatures over 200 °C. The scope was the thermal behavior of the polymer part, and if there was no direct information available on the behavior of WPCs, information available on pure HDPE polymers was used.

During the preliminary testing of the composite material, visible cracks started to form at a temperature proximate to the melt temperature, as seen in Fig. 2.

Fig. 2. The effects of temperature on product quality. The test specimens were heated from 150 and 125 °C before pressing. At 125 °C, visible cracks were observed and the surface finish was rough in comparison to the specimen at 150 °C.

This finding supports the idea that the melt temperature can be marked as a reference for the production. The extrusion temperature of the composite material was 170 to 190 °C, while the typical melt temperature of HDPE is at 130 to 137 °C (Askeland *et al.* 2009).

For further information, the flexural modulus of the composite material was tested with a three-point system where a weight was positioned at the center of the specimen and the temperature of the environment was increased slowly while the displacement was measured. The measurement could only be reasonably measured up to 120 °C because material creep behavior was observed to noticeably distort the results. The dashed line in Fig. 3 represents the extrapolation of the measured curve.

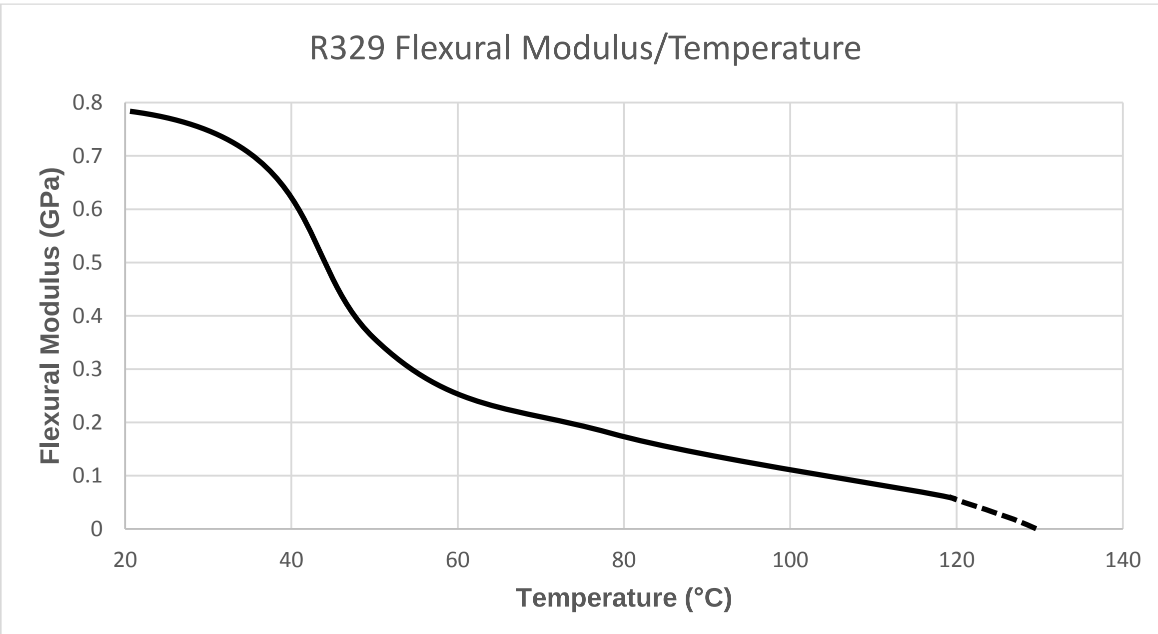

Fig. 3. Measured flexural modulus of the composite material in terms of temperature. The dashed line represents the temperature where the material started to have significant creep behavior, extrapolated from the measured results.

Forming and cutting were selected as different stages in the evaluation of the cooling, as they are heavily temperature-influenced operations. The technique in forming WPCs resembles compression molding closely, and it was used as a reference at this stage. Stokke *et al.* (2014) stated that compression molding is a process in which a heated polymer is compressed into a preheated mold, taking the shape of the mold cavity and cured by heat and pressure applied to the material. A pre-weighed amount of a polymer mixed with additives and fillers is placed into the lower half of the mold. The upper half of the mold moves downward, pressing on the polymer charge and forcing it to fill the mold cavity. Long (2007) list two possible methods for forming material analogical to WPCs, a thermoplastic composite (TPC). The two methods are isothermal and non-isothermal. In the isothermal method, both tools are heated over the melt point of the desired material, while in the non-isothermal method, both tools are kept cold. Long (2007) list the advantages of the non-isothermal process to be a shorter cycle time and improved productivity over the isothermal process; therefore, it was used in this study.

In the cutting operation, a flat product is punched or trimmed out from the material using the shear force of tools. This process can be either matched metal punching with matched die molds or done using a steel rule die. Engelmann (2012) lists better accuracy of products and larger production volumes possible with matched metal punching, and it was used in this study. The total process time was divided into specific timeslots in each process stage to determine the optimal temperature for each stage. Similar partial analysis of the cooling curve is presented also in Sonmez and Eyol (2002), where the time intervals were established between specific adjacent key points describing the progress of the manufacturing process.

A prototype production system called LUT KompoLine shown in Fig. 4 was used in the evaluation of manufacturability. The system consists of two moving press units, each consisting of an Exlar model GSX60-1005 electric actuator for pressing with 55 kN of press force and a Tecnotion linear motor TL12 with 1 kN of linear force for moving the press units. Both units move on a 2-m magnetic track. The press units work in the flying shear principle, in which both units steadily follow a constantly moving raw material web.

Fig. 4. LUT KompoLine press system used in the evaluation of manufacturability in cooling

RESULTS AND DISCUSSION

The results of the cooling experiments are combined in the following graphs with indicated average and bandwidth of the measurements.

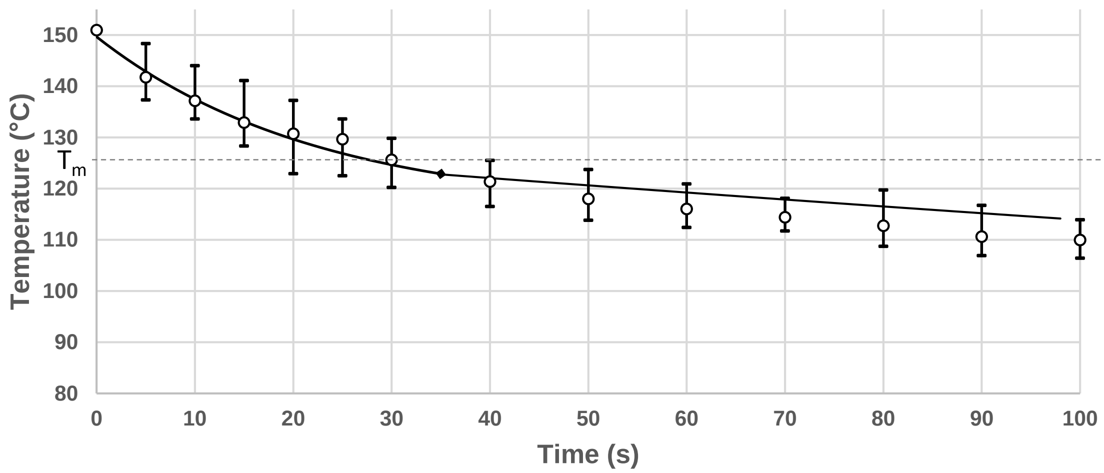

Fig. 5. Measured cooling and an overlaid curve fit with the bandwidth of the measurement indicated

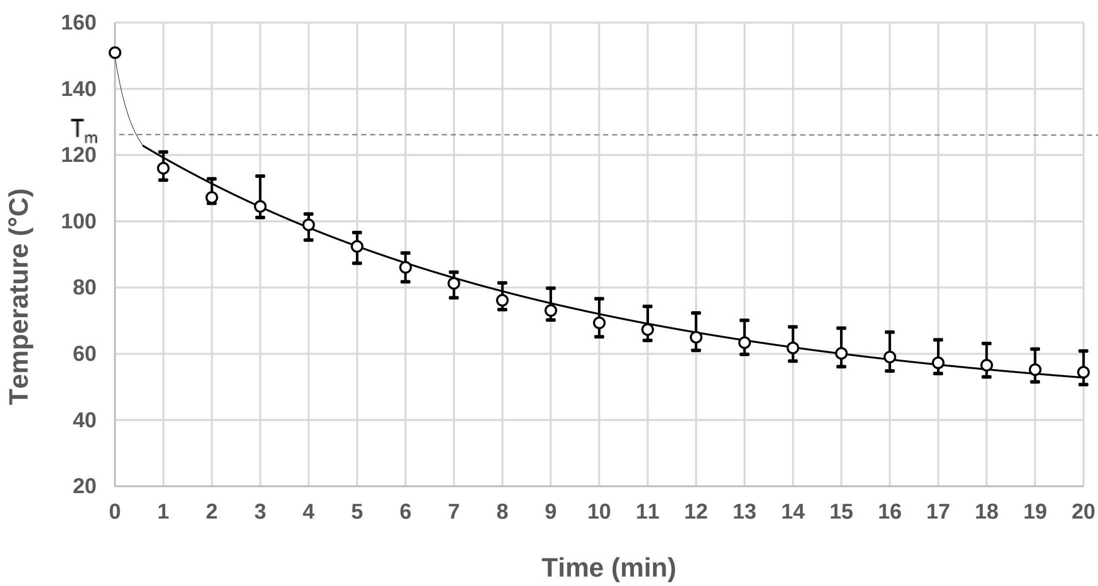

Fig. 6. Measured cooling and an overlaid curve fit with the bandwidth of the measurement indicated

The cooling curve fit was divided into two curves, shown in Figs. 5 and 6, based on the observation of distinct cooling rates near the melt temperature at 125 °C. The bandwidths of the measurements were typically 10 to 15 °C. Similar averages and bandwidths were obtained regardless of the location of the sensor in the specimen, and the measured data are not separated in terms of measurement location in these figures.

The curves were fit into exponential functions for simplicity, and their error sum of squares (SSE) was found to be minimal in comparison to other functions in the MATLAB curve fit package. The basic form of the exponential function formula is:

$$y = ae^{bx} + ce^{dx} \tag{1}$$

Based on the calculated curve fitting, the following curves were obtained:

$$\begin{cases} T = 78.15e^{-0.001926t} + 49.86e^{-0.00008413t} & t \geq 36 \\ T = 33.95e^{-0.04459t} + 115.7e^{-0.000007488t} & t < 36 \end{cases} \tag{2}$$

Equation 2 is the cooling curve, where *t* is in seconds from the start. The curve hits the hot melt temperature of 125 °C at 36 s.

Table 1. Curve Goodness of Fit Values

	SSE	R-square	Adj. R-square	RMSE
Curve 1	5643	0.8876	0.887	3.242
Curve 2	4.84e+05	0.98	0.98	3.012

Cooling rates (°C/s) were calculated as derivatives, and the following functions were obtained:

$$\begin{cases} \Delta T = -1.51383e^{-0.04459t} + 0.000866362e^{7.488\times10^{-6}t} & t \geq 36 \\ \Delta T = -0.150517e^{-0.001926t} - 0.00419472e^{-0.00008413t} & t < 36 \end{cases} \tag{3}$$

Equation 3 is the cooling rate, where *t* is in seconds from the start. The curve hits the hot melt temperature of 125 °C at 36 s.

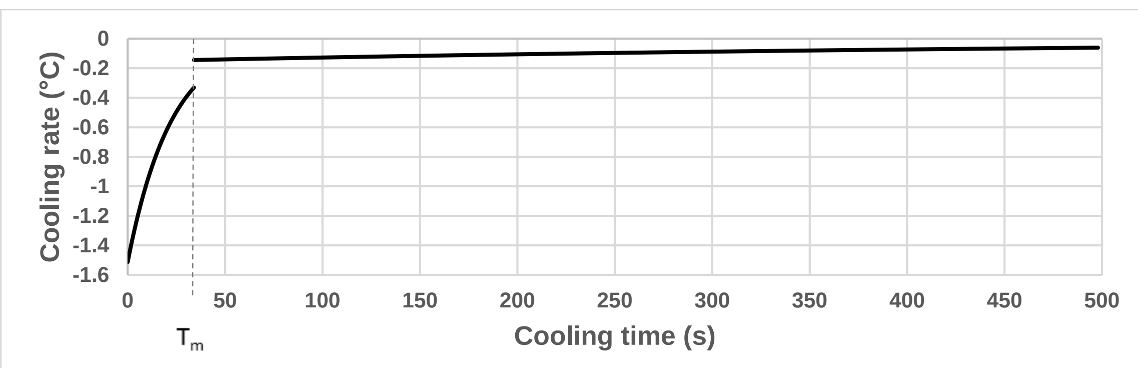

Fig. 7. Calculated cooling rates. The gap between the cooling rates at the melt temperature (T_m) is caused by the curve fit approximation and is not an actual phenomenon.

In the beginning, the cooling rate started to descend quickly from 1.5 to 0.3 °C/s, until it hit the hot melt temperature of 125 °C of the composite material at 36 s. After this event, the calculated cooling rate descended from 1.15 to 0.6 °C/s in 500 s. This phenomenon could be attributed to the fact that linear macromolecules such as polyethylene exhibit a rapid jump in heat capacity at initial point of polymer crystallization Gaur and Wunderlich (1981).

The gap between the cooling rates at the melt temperature was caused by the curve fit approximation, and is not an actual phenomenon.

With respect to the strength of WPCs, Klyosov *et al.* (2007) state that that the flexural strength of HDPE-based composite deck boards is generally reduced by 30% to 60% as the temperature changes from ambient to 55 to 60 °C. Askeland *et al.* (2009) state:

> "at melting point of polymers the strength and modulus of elasticity are nearly zero and the polymer is suitable for casting and many forming processes. Below the melting temperature, the polymer chains are still twisted and intertwined. These polymers have an amorphous structure. Just below the melting temperature, the polymer behaves in a rubbery manner. When stress is applied, both elastic and plastic deformation of the polymer occurs. When the stress is removed, the elastic deformation is quickly recovered, but the polymer is permanently deformed due to the movement of the chains. Some of this deformation is recovered over a period of time. Thus, many polymers exhibit a viscoelastic behavior. Large permanent elongations can be achieved, permitting the polymer to be formed into useful shapes by molding and extrusion."

Based on Klyosov (2007) and Askeland *et al.* (2009) it can be said that flexural strength/modulus is a very temperature-correlated characteristic of WPCs and HDPE and is used in the evaluation of the manufacturability of WPC products.

The measured cooling curves are connected to the measured flexural modulus curve presented previously in Fig. 3 in Figs. 8 and 9. Manufacturability is then inspected separately for forming, cutting, and packaging.

During the forming stage, a three-dimensional product is formed by pressing. During this period, the material should remain in a plastic region over the melting point. Based on the flexural modulus, the melt temperature, and the preliminary results, it can be said that the good forming area originates from the beginning and lasts only 12 s. In an analogical forming process with TPCs by Long (2007), a similar observation can be made.

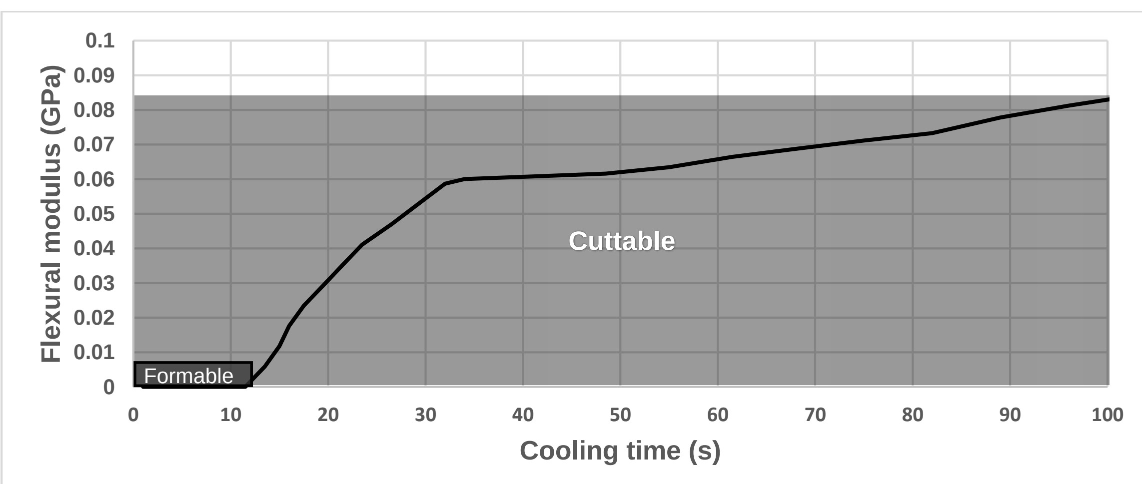

Fig. 8. Flexural modulus *vs*. cooling time overlaid by manufacturing slots

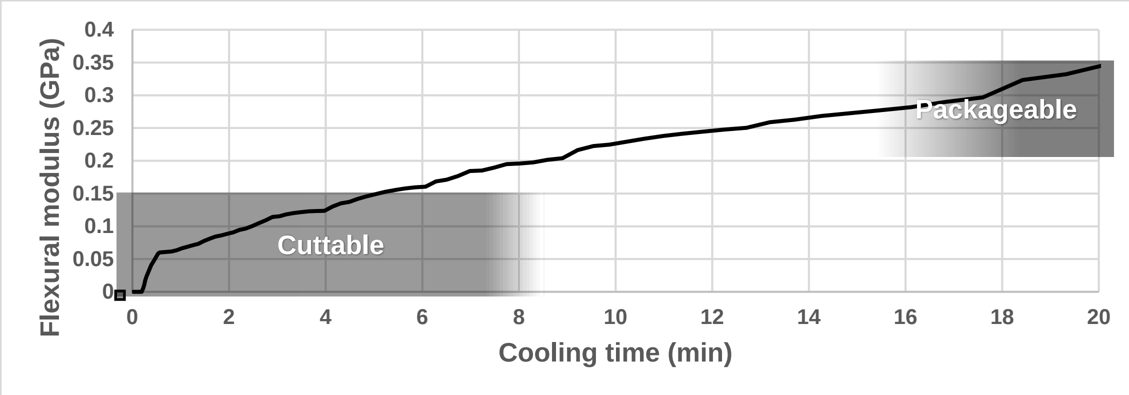

Fig. 9. Flexural modulus *vs*. cooling time overlaid by manufacturing slots

The cooling of the product during the forming stage is affected by the material selection of the tools and the dwell time. For the benefit of product quality, the material should be cooled during forming. In an analogous process of plastic molding, aluminum is often used as the tool material, as it has five times the heat conductivity of steel (Vlachopoulos and Strutt 2002). The disadvantage is that rapid cooling will induce material shrinkage, and it is recommended to anneal the products after processing (Klyosov 2007). During forming, it is important to keep the material at a uniform temperature throughout the product to avoid thermally induced stresses and cracks, which were found to have an effect on product quality and shrinkage in a study by Sonmez and Eyol (2002). The *Handbook of Plastic Processes* (Harper 2006) also states, regarding plastic composites in general, that considering the influence of temperature uniformity on shrinkage, as the thickness uniformity of the part and mold temperature uniformity increase, the less prone the part will be to warp. From the perspective of forming, the reduction in heat gradients can be best done by having the same heat conductivity in both pressing tools and having even material thickness across the product.

Based on the preliminary results of cutting, trimming, and the research done with HDPE by Gent and Wang (1996), it can be said that increasing the temperature makes cutting easier, and thus the area of good cuttability starts at the zero time point and has no clear lower limit for temperature. The preliminary results indicated that at 80 °C or 0.2 GPa, the material started to show brittleness around the cutting edge, and this temperature was set as the lower limit in this study. In natural cooling, this translates into a manufacturing window of 7 min. As the cutting operation is often for two-dimensionally shaped products, there is not a great need to cool the product to retain the form. Based on the preliminary results and information from thermoforming manufacturing with polymers (Engelmann 2012), a zero clearance between the shearing edges of the tools is preferred. This presents challenges in terms of the maintenance required to keep the tools sharp during continuous operation. Saloni *et al.* (2011) has investigated the tool wear on WPCs and has found that pigments are an issue with otherwise moldable materials. In addition to tool wear, heat expansion has a significant role in the management of zero clearance and should be taken into account during the process of tool design.

During the packaging stage, the products should not be deformed or scratched by stacking or wrapping. For this stage, a failsafe temperature would be room temperature. In open system cooling tests, this temperature was achieved only after 3 h and 10 min. As this period is too long for economical production, according to the preliminary results, there is a possibility to start stacking the material at 30% of the flexural strength at 60 °C with acceptable product quality. This time window starts at 16 min in natural cooling but is often easily achievable during material forming, as the tools conduct the heat away easily in a few seconds.

The manufacturing time windows obtained were evaluated using the KompoLine test production press system with example work cycle time shown in Fig. 10. Web speed has a key role in WPC post-production, based on the fact that the extruder is capable of producing either 60 kg or 600 kg of material in an hour.

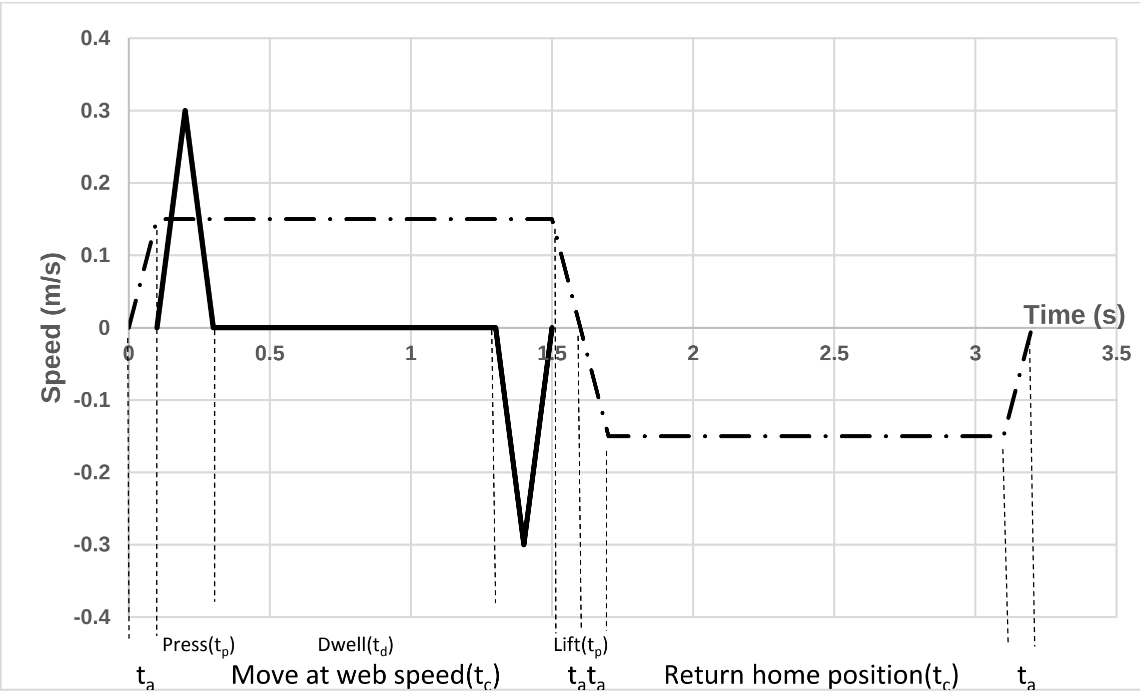

Fig. 10. Structure of KompoLine press cycle with time segments listed

The work cycle consists of accelerating the press unit to match the incoming web speed t_a, moving the press tool down t_p, keeping the tools together for the dwell time t_d, lifting the tools up t_p, stopping and reversing the press unit 2x t_a, returning the press unit back to the home position concurrently with the second press unit moving forward t_c, and finally stopping the unit t_a. Moving the press up and down is the only time constant that is independent of the web speed. Table 2 lists the effects of the web speed for waiting time, dwell time, and total cycle time based on times from the LUT KompoLine test press.

Table 2. Manufacturability Window Evaluation with Times from the KompoLine Press Unit System

Web speed (m/s)	Waiting from extruder (s)	Linear acceleration time (t_a, s)	Press down/up time (t_p, s)	Forming starts (s)	Maximum dwell time by line (t_d, s)	Total cycle time (s)
0.4	0.44	0.60	0.32	1.36	0.20	3.32
0.15	1.17	0.10	0.32	1.59	2.30	5.10
0.04	4.38	0.05	0.32	4.75	15.00	30.25
0.017	10.29	0.05	0.32	10.67	38.00	76.25

In Table 2, waiting time measures how much time has passed before the material reaches the center of the 350-mm tool unit from the extruder nozzle.

Based on the waiting time of material from the extruder, 14 mm/s is the slowest possible speed for successful forming operation with the LUT KompoLine system. The relation between tool center distance and minimal feed speed is illustrated in Fig. 11.

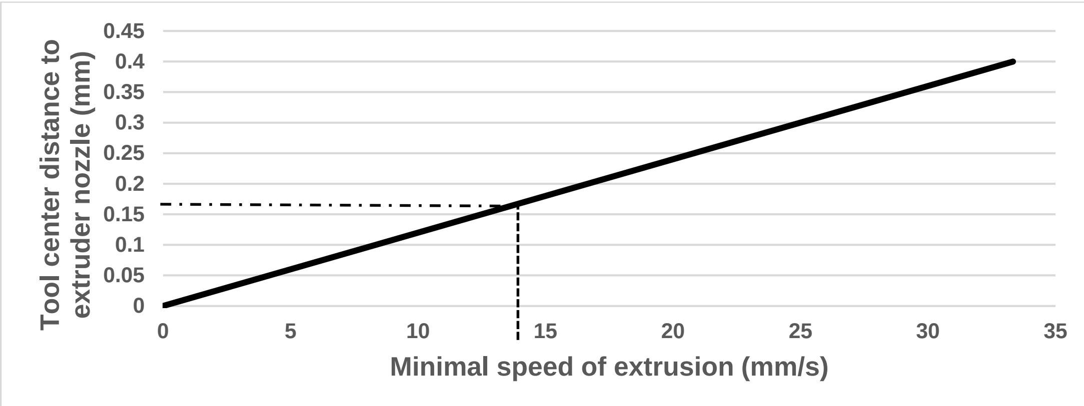

Fig. 11. Relationship between tool center distance to the nozzle and minimal speed of extrusion. Minimal feed time for LUT KompoLine with 350-mm tool width is highlighted.

From the perspective of productivity and cooling, faster web speeds are better. The equipment used in the example case set the upper limit at 0.4 m/s. At this speed, the tool dwell time was at the absolute minimum.

A study by Prisco (2014) shows that the measured heat capacity of WPC50, a material similar to the composite material, has a heat capacitance of 0.35 kW/mK at 20 °C, decreasing to 0.3 kW/mK at 80 °C. These values make WPCs a heat-insulating material and indicate a slightly decreasing trend in the heat capacity with increasing temperature. As WPC50 was only measured to 80 °C, the heat capacity of pure HDPE presented in Gaur and Wunderlich (1981) was also used to approximate the heat capacity of the composite material at higher temperatures. Based on the given function, the heat capacity of HDPE increases curvilinearly from 2 Jg/K at room temperature to 8.5 Jg/K at 150 °C. To evaluate the heating power needed to keep the material at a constant temperature before the forming operation in a uninsulated environment, the cooling power was calculated from the measured cooling curves using the known heat capacities of WPC50 (Prisco 2014) and HDPE (Gaur and Wunderlich 1981).

Figure 12 indicates that at the beginning, the cooling power is 14 kW/m^2, decreasing rapidly to 3 kW/m^2 at the melting point. After the melting point, the cooling power decreases slowly to 400 W/m^2 in 20 min at 60 °C. To minimize distortions caused by the heat gradients across products, the level of heat loss at the start could be reduced easily by insulating the section between the nozzle and the press unit, and using resistor heaters during conveying the composite material and infrared heaters with a thermostat in the adjustment of the temperature.

After and during forming, the interest is in cooling the products as quickly as possible to keep the desired formed geometry. Typically, when the products exit the forming tools, they are still a temperature of 85 to 100 °C. Dropping the temperature rapidly to room temperature would require artificial cooling, or increasing the heat conductance of the forming tools or the dwell time. As production and cost effectiveness are directly associated with the cycle time of each product and the length of the production line, having shorter cooling time makes the production not only faster, but also presents the possibility of reducing the line length. Faster product cooling can be achieved either with air or water sprays. Water does not noticeably affect the WPC product. Klyosov (2007) states that WPC with HDPE has only 0.7% to 2.0 % water absorption in 24-h submersion compared to 20% to 25% in pure wood; therefore, in typical commercial WPC deck profile lines, there is a cooling tank with water sprinklers right after the extrusion nozzle. To shorten the process, Escobedo and Fernández (2012) state that to improve polymer cooling, the material should be cooled from both sides. Having the material submerged under water would be the easiest way to achieve this.

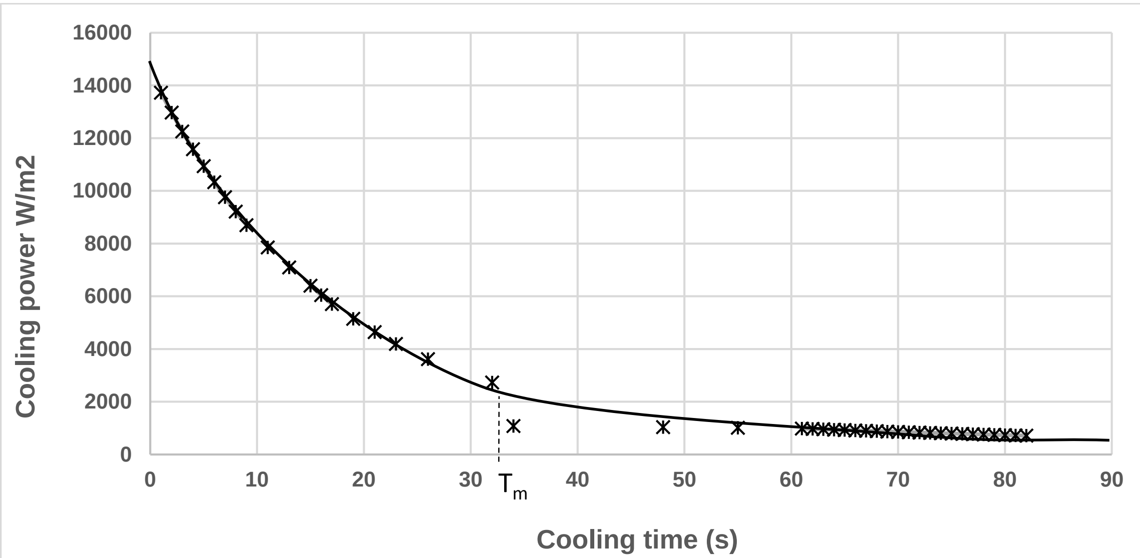

Fig. 12. Calculated cooling power in W/m^2, calculated using the heat capacity of HDPE and the measured cooling rate of the composite material. T_m indicates the melting point of the material.

As convection is the mode of energy transfer between a solid surface and adjacent liquid or gas that is in motion and involves the combined effects of conduction and fluid motion (Cengel 2002), higher web speeds could have an effect on cooling in addition to heat gradient-induced convection and heat radiation that were included in measurements. However, due to limits of the testing environment, velocity-induced convection was not simulated in the stationary experiments presented in this paper. Also as typical industrial extrusion speeds are relatively slow, in the range of 10 to 100 mm/s, it can be said that the effect of convection would have a minimal effect at this level; however, at higher speeds, there premature cooling could be caused by this phenomenon.

CONCLUSIONS

1. Cooling tests with 20 sheets of 3-mm-thick wood plastic composites (44% fiber, 50% PE, 3% coupling agent, 3% lubricant) were successfully conducted from the extrusion nozzle temperature of 150 °C to room temperature, and the resulting cooling curves were fit into two exponential functions separated by the material melting temperature. The measured bandwidth of the measurement points was observed to be independent of the location of the measurement and there was not an observable difference in the

bandwidth or in the average of the measure points from the edge or the center of the sheet.

2. The production cycle time results indicated that the material can be non-isothermally formed and cut in times that can be achieved with uninsulated WPC post-production lines coupled directly to the extrusion equipment if the extrusion speed and cross section of product is selected correctly. It was found out that the cooling sets limits for the slowest web speed attainable, as the products have to be formed before the temperature drops under the melting temperature. Based on the natural cooling of the material, it was found out that 14 mm/s is the slowest possible speed for the extrusion in the LUT KompoLine press, with a press unit width of 350 mm.

REFERENCES CITED

Askeland, D., Pradeep, R., and Fulay, P. (2009). *Essentials of Materials Science and Engineering* (2nd Ed.), Cengage Learning, Boston, MA.

Brucato, V., Piccarolo, S., and La Carrubba, V. (2002). “An experimental methodology to study polymer crystallization under processing conditions. The influence of high cooling rates,” *Chem. Eng. Sci.* 57(19), 4129-4143. DOI: 10.1016/S0009-2509(02)00360-3

Cengel, Y. A. (2002). *Heat Transfer: A Practical Approach* (2nd Ed.), Mcgraw-Hill, New York.

Engelmann, S. (2012). *Advanced Thermoforming: Methods, Machines and Materials, Applications and Automation*, John Wiley & Sons, Hoboken, NJ.

Escobedo, R., and Fernández, L. A. (2012). “Optimal cooling strategies in polymer crystallization,” *J. Math. Chem.*50(2), 313-324. DOI: 10.1007/s10910-011-9803-x

Gaur, U., and Wunderlich, B. (1981). “Heat capacity and other thermodynamic properties of linear macromolecules. II. Polyethylene," *Journal of Physical and Chemical Reference Data.* 10(1), 119-152.

Gent, A. N., and Wang, C. (1996). “Cutting resistance of polyethylene,” *J. Polym. Sci. Pol. Phys.* 34(13), 2231-2237. DOI: 10.1002/(SICI)1099-0488(19960930)34:13<2231::AID-POLB12>3.0.CO;2-6.

Harper, C. A. (ed.) (2006). *Handbook of Plastic Processes*. Wiley-Interscience, Hoboken, NJ.

Klyosov, A. A. (2007). *Wood-Plastic Composites*, Wiley, Hoboken, NJ.

Liu, Y., and Gehde, M. (2015). “Evaluation of heat transfer coefficient between polymer and cavity wall for improving cooling and crystallinity results in injection molding simulation,” *Appl. Therm. Eng.* 80, 238-246. DOI: 10.1016/j.applthermaleng.2015.01.064

Long, A. C. (ed.) (2007). *Composites Forming Technologies*, Woodhead Publishing, CRC Press, Boca Raton, FL.

Prisco, U. (2014). “Thermal conductivity of flat-pressed wood plastic composites at different temperatures and filler content,” *Sci. Eng. Compos. Mater.* 21(2), 197-204. DOI: 10.1515/secm-2013-0013

Saloni, D., Buehlmann, U., and Lemaster, R. L. (2011). “Tool wear when cutting wood fiber-plastic composite materials,” *Forest. Prod. J.* 61(2), 149-154.

Sonmez, F. O., and Eyol, E. (2002). "Optimal post-manufacturing cooling paths for thermoplastic composites," *Compos. Part A-Appl. S.* 33(3), 301-314. DOI: 10.1016/S1359-835X(01)00133-6

Stokke, D. D., Wu, Q. L., and Han, G. P. (2014). *Introduction to Wood and Natural Fiber Composites*, John Wiley & Sons, Chichester, West Sussex, UK.

Tan, S. B., Hornsby, P. R., McAfee, M. B., Kearns, M. P., and McCourt, M. P. (2012). "Water spray cooling of polymers," *Polymer Engineering & Science* 52(5), 1069-1080. DOI: 10.1002/pen.22173

Vlachopoulos, J. and Strutt, D. (2002). *Plastics Technician's Toolbox*, Society of Plastics Engineers Incorporated, Bethel, CT.

Wijskamp, S. (2005). *Shape Distortions in Composites Forming*, Ph.D. thesis, University of Twente, Enschede, Netherlands.

Yang, W., Xie, Y., Wang, H., Liu, B., and Wang, Q. (2013). "Impacts of freezing and thermal treatments on dimensional and mechanical properties of wood flour-HDPE composite," *J. Forest.* 24(1), 143-47. DOI: 10.1007/s11676-013-0334-0

Article submitted: October 2, 2015; Peer review completed: September 20, 2015; Revised version received and accepted: October 2, 2015; Published: October 14, 2015.
DOI: 10.15376/biores.10.4.7970-7984