# Method for Limiting Waste in Wood Plastic Composite Post-Production by Means of Press Unit Control Parameters Utilizing Temperature-Related Dimensional Changes

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Wood plastic composites are an interesting development in composite materials. They have gained wide market interest recently because of their sustainable material sources and beneficial material properties. Because thermosets or thermoplastics are involved in the composites, the material is temperature-dependent and susceptible to considerable dimensional changes with the variation of temperature. To minimize waste generation and enable reheated material post-processing, the distortion and displacement of the composite material has to be controlled precisely in different temperature ranges. This article studies ways to control this displacement and proposes a solution with an odometer and polynomial curve fit.

*Keywords: WPC post-processing; Positioning; Stamping; Shrinkage*

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## INTRODUCTION

Wood plastic composites (WPCs) have recently gained an increased market share in a number of customer products, such as flooring elements and fencing, because of their desirable material properties, including consistent quality, splinter-free structure, and good durability, as well as the use of sustainable material sources while remaining economically viable. Currently, the WPC products available on the market are mostly limited to extruded profiles (Klyosov 2007). However, there is increasing demand for more complex product shapes and geometries, which need post-extrusion processing after the material fabrication stage. The tightening of environmental legislation in the European Union, with its demands for greater utilization of different waste segments and reduction in landfill waste, means that WPCs that can utilize and recycle municipal and building waste (Carroll *et al*. 2001; Cruz-Estrada *et al*. 2010). Thus, the area of WPCs are an increasingly interesting research area.

Previous studies have shown that WPCs can be post-formed, and natural cooling does not set strict limitations for the manufacturing process (Matthews *et al*. 2015; Toghyani *et al*. 2016). It has been demonstrated that thermoplastic WPCs can be recycled by a re-extrusion process (Sarabi *et al*. 2014), and also that the properties of WPCs can improve during material re-processing (Sarabi *et al.* 2012). It has been noted that a relationship between plastic displacement and residual stress exists in thermoplastic composites and that thermal and resin cure shrinkage strains, gradients in the temperature, resin degree of cure, resin pressure gradients, and tooling mechanical constraints are the most responsible factors causing displacements in plastics. It has also been stated that thermal mismatches at different directions and plies are the major source of these stresses (Baker *et al*. 2004). Moreover, it has been suggested that material anisotropy, material property gradients, and stress state gradients play a large role in causing distortion in the composite material (Radford and Rennick 2000). The effect on thermally induced deformation has been studied in fiber composite laminates, where it has been shown that the matrix has a major role in shrinkage during the curing process (Wang *et al*. 2012), and the effect on thermal expansion and cure strain has been investigated in carbon fiber-reinforced plastics (Ito *et al*. 2015). Theoretical modeling of cure shrinkage has been studied with a thermosetting composite material by Ersoy and Tugutlu (2010). Warpage is also listed as one of the most common causes of manufacturing distortion in composites. Radford and Rennick (2000) state that there are two major mechanisms that cause warpage: thermoelastic (thermal expansion) and non-thermoelastic (curing). Shrinkage and thermal expansion are known phenomena in WPCs that have been studied in outdoor surface decking (Klyosov 2007). While thermal expansion is reversible, the shrinkage effect caused by curing is not.

Stamping of thin composite sheets is a common post-processing way to produce aircraft parts from composite materials, where accurate positional control of the material is needed (Baker *et al.* 2004), and the same approach was employed in the present work. Roll-to-roll industries, such as paper mills, have always been interested in material web handling and control. For example, the dynamics in lateral movement and web tension control have been studied by Chen *et al.* (2009). Material web positional control has also been studied with respect to the needs of printed electronics, where the web has to be positioned precisely for the electronic components (Noh *et al.* 2013).

In stamping of WPC products, the actual distance between stamped products is defined by the material properties and uses the positioning method illustrated in Fig. 1. Currently, the actual distance has to be set higher than the minimal distance because of the temperature-induced displacement of the material.

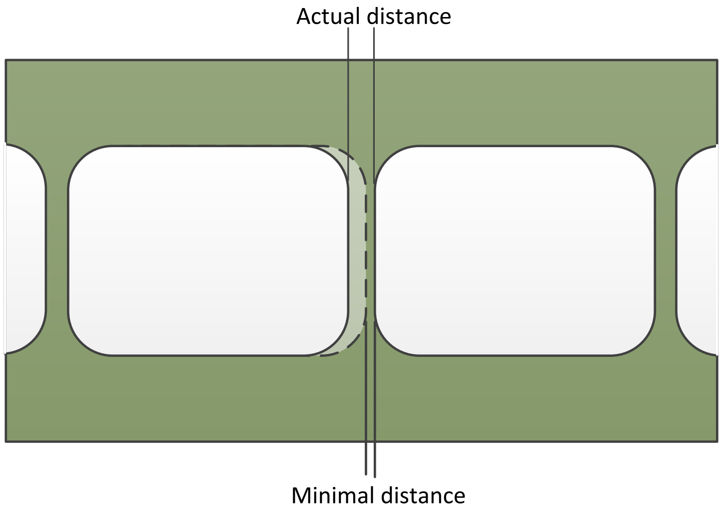


**Fig. 1.** Composite material waste web. The illustration is from the top side of the material waste web.

The possibility of using WPC material fabricated elsewhere, cooled, and then reheated at the post-production location for the stamping process has so far not been investigated. This kind of utilization of prefabricated WPC is a novel method that consists of separating fabrication and post-processing to different locations. This way, less expertise is needed for controlling the process at the site of the post-processing plant. To utilize reheated material optimally without excess waste, a method has to be developed to control the displacement and distortion of the reheated material based on the composite material properties. For example, to counter the effects of these properties, the actual stamping distance between the products on the material web has to be set higher than the minimal distance because of temperature-induced displacement.

The commonly used method, which involves conditioning of composite products in an oven for an extended period of time to reduce the effect of shrinkage; this is often time- and energy-consuming at the production stage. If this stage can be omitted and the utilization of waste rim improved, then there is potential to expand production and make cheaper products supporting the production and usage of wider array of customer products from recycled WPC materials. In addition, knowing the reheating induced displacement and controlling the process accordingly makes it possible to utilize prefabricated composite materials and enables more precise multi-stage pressing of products.

## EXPERIMENTAL

A wood thermoplastic composite material with 50% high-density polyethylene (HDPE) derived from recycled plastic bags and 44% wood flour was used in the specimens for this study. The composition of the composite material is presented in Table 1. This composite material was selected because of promising preliminary formability tests for a very wide range of customer applications and because the material has a common fiber-to-matrix ratio for thermoplastic WPCs, allowing general evaluation of thermal expansion and shrinkage in the WPCs. Thermoplastic (HDPE) was selected as the polymer matrix because of the reheating possibility and good availability in recycling. Spruce wood fibers were ground and sieved with a MESH 20 (0.85 mm) sieve to uniform wood flour.

**Table 1.** Measured Material Properties of the Tested Composite Material and its Major Ingredients

| | Composition | Hardness | Tensile strength | Modulus of elasticity |
|---|---|---|---|---|
| **Composite material** | 50% HDPE, 3% MAPE, 3% lubricant, 44% Wood flour MESH 20 | 5.06 HB | 21.5 MPa | 4.5 GPa |
| **HDPE** | | | 15.0 MPa | 0.8 GPa |
| **Wood flour** | | 2.6-7.0 HB | 40.0 MPa | 11.0 GPa |

Tensile strength and modulus of elasticity were measured with a Z020 material testing device (Zwick-Roell, Germany). Measurements of HDPE and Wood flour were conducted before granulation.

In the testing procedure, a material sheet of the composite material with a length of 675 mm ± 0.1 mm was heated in an electrical oven with an accuracy of ± 1 °C for 40 min. The temperature was gradually lowered in steps of 10 degrees, and the length was measured visually using a line gauge. The sheet size was selected based on the internal dimensions of the oven. The experiment was carried out with five different sheets of the same dimensions, each sheet having four reheating cycles. The visual error margins are ± 0.2 mm.

In defining the minimum stamping distance between the products, a circle-shaped symmetrical product with a diameter of 50 mm (± 0.05 mm) was stamped repeatedly while varying the distance. In preliminary experiments, it was found that the minimal distance of the material between products was dependent on the temperature. With the selected material, the minimal distance measured with a caliper was 1 mm ± 0.1 mm at 160 °C and 2.5 mm ± 0.1 mm at room temperature (24 °C). These values set the lowest possible distance between the stamped products.

The displacement results of the experiments was combined into curves refined in Excel 2013(Microsoft Corp., USA) to determine the standard deviation, average, and polynomial curve function.

### Post-Process Stamping Line

To review the results on a larger production scale, a practical implementation of the control system is proposed on a post-production system meant for stamping WPC sheets. This line consists of two press units moving on a linear table, as illustrated in Fig. 2. To minimize the horizontal component of vibration, a second press-forming unit traveling in the opposite direction has been added. This in turn makes it possible to achieve better positioning accuracy and thus a better product. It is also possible to utilize both press units in multi-stage forming, enabling more complex shapes and functionality in WPC products.

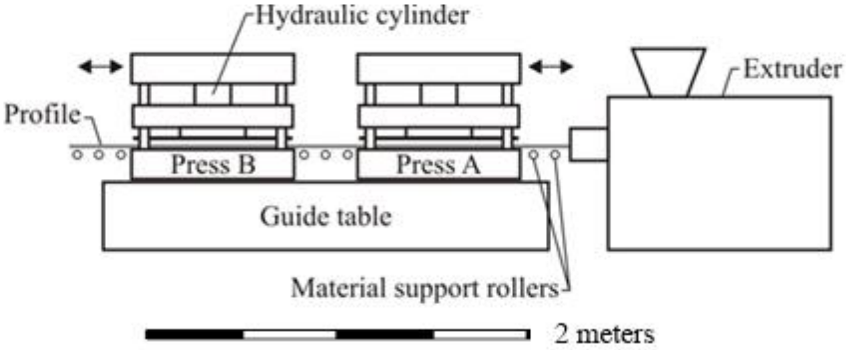


**Fig. 2.** Process overview of the proposed design with two press-forming units at an estimated scale. The extruder can be replaced with a reheating oven if the composite material is produced in a different location.

## RESULTS

The results of the shrinkage experiment based on reheating cycles are combined in Fig. 3 with the indicated average and bandwidth of the measurements.

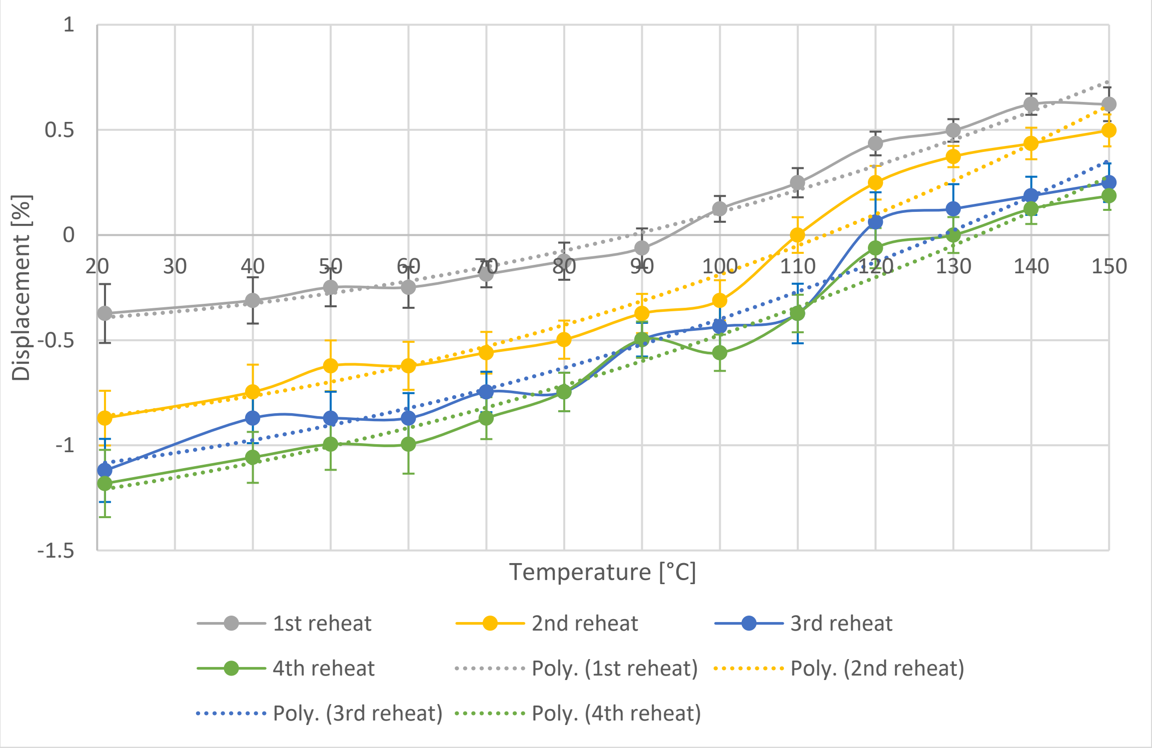


**Fig. 3.** Curves of measurement of average shrinkage for different reheating cycles with second-order polynomial fit curves and normal deviations visible. Displacement value 0% corresponds to the original material length at room temperature.

In Fig. 3, it is notable that the melting point of HDPE is visible in the curves at 120 °C. Otherwise, the curves generally follow second-degree polynomial functions curvilinearly. The reheating cycles affect the overall length at room temperature, with a total shrinkage of 1.2% after four reheating cycles. After three cycles, the material shrinkage curves start to approach a limit where the material length is not affected by the additional reheating cycles.

The following polynomial equations were generated from the data:

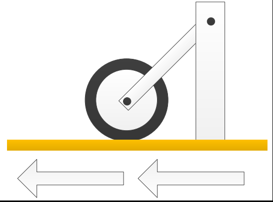
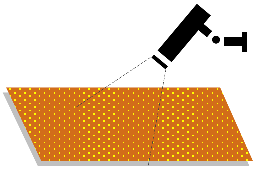
1st reheating: $y = 5E\text{-}05x^2 + 0.0006x - 0.4245$; $R^2 = 0.9758$
2nd reheating: $y = 6E\text{-}05x^2 + 0.0014x - 0.9139$; $R^2 = 0.9704$
3rd reheating: $y = 5E\text{-}05x^2 + 0.0026x - 1.1595$; $R^2 = 0.9625$
4th reheating: $y = 5E\text{-}05x^2 + 0.0038x - 1.308$; $R^2 = 0.9783$

The equations provide second-degree polynomial functions for the relationship between displacement of the original length and the material temperature. These functions are used as a basis for controlling the units according to the temperature. Displacement reached a total of 1.2% after four reheating cycles. Material moisture content was measured to be 2.4%, 1.7%, 1.5%, and 1.4% after each reheating cycle. This indicates that although the material was relatively dry at the beginning, some moisture still boiled off during each reheating cycle. It is uncertain whether these numbers included volatile organic compounds (VOCs) boiling off the material.

## Proposed Methods for Material Web Control

There are multiple ways to position the moving units according to the thermal displacement. Precise web tension control is not possible because of the molten state of the composite material; therefore, the process machinery must be able to follow the web by other means. It is not possible to use commonly used nip rollers as the method for positioning, as the possible geometry of composite material sheet is not limited to rectangular cross section in order to take a full advantage of extrusion process. For these reasons, the material is conveyed on a conveyor belt. Table 2 lists possible control methods for operation with conveyor belt.

**Table 2.** Alternative Ways to Control the Modules, with Advantages and Disadvantages Listed

| Method | Measuring wheel | Sprocket Holes | Camera measurement |
|---|---|---|---|
| Principle |  |  |  |
| Advantages | Cheapest method. Material color does not influence the result. | Simple. Material color does not influence the result. | Material is not imprinted by a sensor and can have a complex profile. |
| Disadvantages | Visible marks in soft material. Temperature must be measured. | Possible distortion. Edge area must be flat. | More expensive. New material must be taught to the system. The surface must have contrast or a visible feature. Background lighting is in a great role. |

A measuring wheel odometer is a commonly used solution in industrial applications. The advantage of this solution is its simple construction, and the disadvantage is that the wheel might slide on low friction-coated WPC material or leave a residual depression on the material sheet.

Sprocket holes or perforations can be utilized on the side of material web, as their shrinkage is relative to the material shrinkage, and a simple control logic can follow the placement of the holes for precise control. Conveying and positioning polymeric materials with similar perforating clamps is a common feature of thermoforming machinery. The disadvantage of such as system is that an additional punching equipment is needed for the perforations and the material shrinking might not be uniform in all directions.

The camera measurement system utilizes visual cues to track the position of material. The major disadvantage of such as system is that material surface should have enough contrast to be trackable, and therefor this system could not be used with monochromatic coating without additional markings on the material.

Based on advantages and disadvantages listed, a measuring wheel was selected for the prototype line setup, as shown in Fig. 4. The pressure of the odometer should be set according to the used composite material in a way that the sensor has enough friction but does not cause traces in the molten material. The temperature of the composite material is monitored with an infrared sensor in each module, and accurate positional control of the modules is achieved with a simple polynomial controller utilizing the second degree polynomial function based on the measured thermal displacement values obtained during reheating cycles.

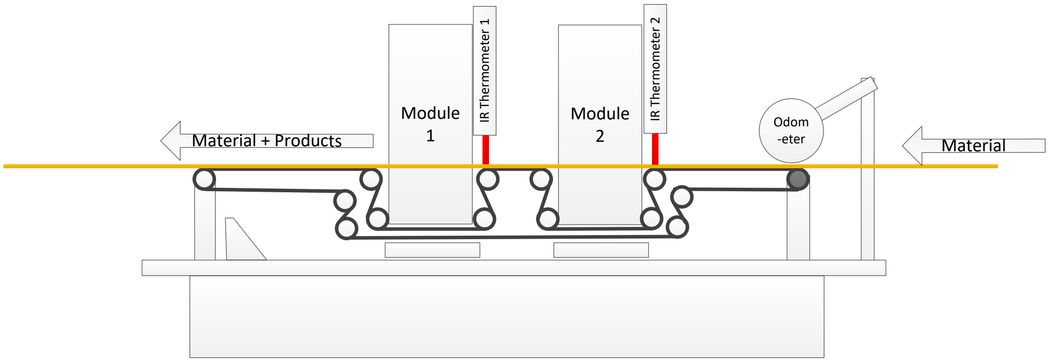


**Fig. 4.** Proposed system for positional controlling two-press unit system in the control of temperature-induced displacements. The material is input from the right side and post-produced with two press units with infrared sensors attached. The odometer follows the distance the material travels and guides the press unit according to the obtained curve function.

## DISCUSSION

The aim of the study is to find a control system that can bring the stamping distance as close as possible to the material limit and enable a more precise multi-stage stamping operation by measuring the material-specific shrinkage after the reheating cycles.

Typical bandwidths of the displacement measurements are between 0.3 % in room temperature and 0.2 % in molten state. This variation can be caused by slight warpage in solidified material that is relaxed in elevated temperatures. The experiments were conducted in a typical factory environment and were aimed at generating knowledge of the material for the design of the post-process stage. As the environmental variables were not strictly controlled, extraneous variables, such as environment humidity, had influence on the result. This limits the usability of the generated data to the inspection of manufacturability and feasibility in indoor factory conditions only. This kind of a variable environment is considered a *fixed operating condition* by Figliola and Beasley (2011) and is often used in engineering measurements.

During curve plotting the 2nd degree polynomial curves were approximated from the measured displacement data. This polynomial function represents expected curvilinear behavior of thermoplastic during cooling phase as documented by Stuart (2002) in a digital scanning calorimetry experiment. The accuracy of curves was reasonably close to the measured averages, while still being simple enough for smooth control operation. However, the material melting peak at 120 degrees is a challenge to be modelled with one polynomial function regardless of the polynomial degree. This could be avoided by having multiple polynomial curves based on a temperature range. This solution would require a more complex logic controller than the recommended polynomial controller.

The results suggest that there was a permanent reduction of 1.2% in the total length of the material after four reheating cycles because of the shrinking nature of thermoplastics. Common values for shrinkage of pure HDPE vary between 1.5% to 5.0%, depending on the crystallinity and the manufacturer (Karian 2003). In this light, it can be said that the selected WPC material considered in this work had less shrinkage compared with pure HDPE polymer.

Manufacturers often anneal the WPC profiles to reduce the final shrinkage of products (Klyosov 2007). On the basis of the present study, annealing the composite material before the reheating cycles could be suggested to minimize the residual shrinking effect. However, in testing with excess temperature of over 120 °C, discoloration of fibers and the tendency of the polymer to migrate to the surface of the material sheet were observed during reheating cycles. This migration of polymers is a known phenomenon, and Segerholm (2007) spotted a similar effect in WPC deck profiles after excess heat was induced. These issues are mostly cosmetic and easily hidden with a coating layer in applications where a high level of structural durability is not required.

It has been noted in previous studies (Rowell 2007; Yeh and Gupta 2008) that in a humid environment, the fiber part of the composite material can swell, causing displacement. In this study, the effect of moisture was not reviewed, as the initial moisture level of the material was already too low (2.4% RH) to cause any noticeable swelling of the product. In addition, it was found that reheating improved material durability because of the mentioned polymer migration behavior (Segerhom 2007; Ovaska 2015). This heat-induced migration can allow polymers to enclose exposed fibers at the surface of the composite material, making the composite water resistant and resistant to swelling.

In addition to the material-defined distance limit, the forming tools set space requirements. For example, to avoid warpage and to produce controlled elongation, a clamp tool might be used to keep the material web tensioned during the forming operation. The clamp tool requires free space around the stamping tool for friction generation to prevent unwanted sliding. This factor makes the actual minimal stamping distance longer than the minimum of the material.

This study was limited to one particular thermoplastic composite material. The material recipe, density, extrusion speed, and downstream pooling have a direct effect on the shrinkage rate of a WPC (Klyosov 2007). However, the used measurement method and logic control can be utilized with other thermoplastic fiber composite materials.

The main challenge of the proposed control method is that the infrared sensors are only able to measure the surface of the composite material, and in a thick material profile of over 5 mm, the core temperature could be considerably (over 30 degrees) higher. In this light, the cooling should be controlled to limit the heat gradients and residual stresses across the profiles by utilizing insulation or heaters around the composite material web. An additional measurement challenge comes from the glossiness of the material, as mirror effect could affect the temperature reading of infrared sensors.

This study concerned only material positioning in the machine direction, and possible lateral movement or lateral shrinkage of the material on the conveyor was not considered. This presents an interesting research topic for the future. The issue might present itself in precise multi-stage forming, where the problem could be overcome by having lateral movement ability in the press units.

## CONCLUSIONS

1. By measuring the material distance in combination to temperature, it is possible to post-process the composite material at a different production location with optimal material usage if material shrinkage during the reheating cycles is known and the methods

proposed in this paper are utilized. This also enables multi-stage pressing if the flying shear technique is utilized in the press system.

2. The results suggest that there is a permanent reduction of 1.2% in the total length of the material based on four reheating cycles caused by the shrinking nature of thermoplastics. It is recommended to limit the material cooling to reduce the displacement of the composite material in multi-press operations.

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