Feasibility Assessment of a Wood-Plastic Composite Post-Production Process: Formability

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Wood-plastic composites (WPCs) – one of a number of promising classes of materials in the manufacturing industries – are experiencing rapid market growth. However, the favorable characteristics of this material and the development of new production processes and post-production processes suggest even greater potential for utilization of WPCs. This paper evaluates the formability of an extruded WPC material comprising nearly 45% wood fiber, 50% thermoplastic, and 5% of other additives in a novel extrusion-based post-production process. The press-forming process described in this work is used to form and cut the pre-determined profile shape to obtain the final product. After preliminary tests to determine the suitable temperature range, dimensions, and roughness range for a post-extrusion hot-pressing process of a sample WPC product, a diverse set of product quality tests were then conducted on pre-heated sheets of WPC material using forming tools attached to a hydraulic press. The forming process had high accuracy with respect to dimensional precision and acceptable repeatability. The forming process also reduced the surface roughness of the material. The test results clearly demonstrated the dependence of final product quality on the quality of the original extruded WPC profiles used, *e.g.*, with respect to the thickness variation of the material.

Keywords: WPC forming; Post-extrusion processing; Surface roughness; Thickness variation

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INTRODUCTION

The term wood-plastic composite (WPC) is rather broad and refers to a wide range of composite materials containing plant fibers that use thermosets or thermoplastics as the bonding matrix. The properties of WPCs depend essentially on the plastic and wood contents. In WPCs, the wood material segment, which can be either wood fiber or wood flour, generally constitutes 30% to 60% of the total material (Klyosov 2007). Recently, use of WPCs has increased because of its many advantageous properties, such as better dimensional stability and higher resistance to decay than regular wooden products (Steward 2007). It also has the advantages of low abrasiveness, high stiffness, wide availability, and biodegradability (Dittenber and Gangarao 2012). WPC material is used in various indoor and outdoor applications, such as decking, railing, fencing, roofing, siding, and landscaping timbers (Ashori 2013).

Wood plastic composites are a good example of modern materials that have great potential to become even more popular through the use of recycled materials, which bring cost benefits because of their low cost, in addition to any environmental considerations

(Ashori and Nourbakhsh 2009). The wide applicability of WPCs and the environmentally beneficial aspects of its use have made the WPC field one of the most active fields of today's plastic industry, which has an average annual growth rate of approximately 18% in North America and 14% in Europe (Ashori 2008).

On the other hand, despite the large amount of wood and plastic waste generated in some countries, in many markets it is hard to observe any development of materials recycling in WPC, and most work on usage of recycled material in WPC is still at an experimental level (Cruz-Estrada *et al.* 2010). Issues such as the lack of trees – the major source of fibrous material – in many parts of the world, increasing demands for these materials, and increased environmental awareness underline the need for active research in the development of WPCs that use waste materials (Stark and Rowlands 2003).

Extrusion is used as a primary fabrication method due to the fact that WPC material production requires mixing and the bonding of materials and heat, which can easily be achieved in a single extrusion process. Also this selection is on the basis of the material properties of WPCs and the productivity benefits of the extrusion process, particularly in view of technical improvements to the extruder in recent decades and the wide range of extruder configurations now available (Favis and Therrien 1991; Bauser *et al.* 2006).

Research on the production of WPC products has tended to focus on the challenges of the WPC extrusion process (Soury *et al.* 2008), the performance of extruded WPCs (Huang *et al.* 2013), and key parameters in extrusion such as fiber size and WPC properties (Migneault *et al.* 2009). Relatively little work can be found in the literature on the post-processing of WPCs (Matthews *et al.* 2015). Because of a lack of development of post-production processes, current WPC products are limited to profiles with uniform cross-section resulting directly from extrusion. To alleviate that constraint and provide greater potential usage of WPC, post-extrusion process would be the solution considering the fact that after extrusion, WPC materials are rigid but still relatively soft which make them suitable for machining or forming. Therefore, post-production processes can be used that may not be suitable for more rigid materials such as wood.

Post-Production Process

Selection of the best method for a post-material production process depends on the nature of the composite material, the production cost, product shape, and desired production rate. In addition, the production line has to meet environmental, material, and production requirements, such as suitable temperature and moisture conditions. Pressing is used as a post-processing method in the paperboard, glass, and sheet metal industries, and press forming of fiber materials has been commonplace for decades. Stamping and drawing are common ways to produce metal products such as coins and car body parts (Schuler GmbH 1998) from sheet metal and tableware from paperboard and glass (Kuusipalo 2008; Groover 2011). Pressing works well compared with other post-process methods, as it is a fast, economical, and simple way of forming products.

Deep drawing consists of pressing a male die into the sheet until it stops against a female die, leaving an imprint on the sheet (Östlund *et al.* 2011). Deep drawing has been used in the forming of coated paperboard, which like WPC is a fiber-based material and has a plastic component. Production issues such as thickness variation and poor surface quality caused by sticking or cracking of material in the production process are likely to be similar for both materials (Leminen *et al.* 2013).

Shaping processes can be divided into forming and cutting. In forming, a shape is formed by pressing or pulling the product against mold units, which generates a three-dimensional product shape. In cutting, a shape is formed by pressing the product against cutting blades, which generates two-dimensional product shapes. Cutting can be performed mechanically, by injection or by focused energy beam. In some cases, it is possible to combine forming and cutting into the same tool, although at the expense of increased complexity and tool cost. A coupled system with a feeding extruder located next to the shaping process is common in the plastic packaging industry but is a novel approach in the manufacturing of WPC products (Toghyani *et al.* 2013; Matthews *et al.* 2015).

One of the objectives of the current study was to determine whether it might be feasible to form WPC material into potentially useful shapes at a temperature equal to or lower than that of the extrusion process. In view of the inherent characteristics of the extruded WPC profiles, another objective of this research was to establish whether the predominant direction of the wood particles affects the post-forming attributes and their directionality.

The post-production process can be considered feasible if it succeeds in effectively forming the desired WPC profiles after the primary production process. To evaluate the formability, variability and control of the post-production process, forming test results were assessed on the basis of measurement of product quality characteristics such as deformation, thickness variation, and surface roughness.

EXPERIMENTAL

Material Properties

The most important material-related challenges in the extrusion process of WPCs are caused by wood moisture content, thermal degradation of wood and associated thermal stress, and a lack of homogeneity (Lesslhumer 2014). In addition, it has been shown that different fiber proportions and fiber lengths not only affect the mechanical properties of the material, but also have considerable influence throughout the WPC manufacturing process (Migneault *et al.* 2009). The material properties of the WPC used in this research are presented in Table 1.

Table 1. Material Properties of the WPC used in this Research, Typical HDPE, and Untreated Wood

	Composition	Hardness (Brinell scale)	Tensile Strength	Modulus of Elasticity
WPC material used for this research	50% HDPE, 3% MAPE, 3% Lubricant, 44% Sawdust MESH 20	5.06 HB	21.51 MPa	4.50 GPa
HDPE			15 MPa	0.8 GPa
Untreated wood		2.6-7.0 HB	40.0 MPa	11 GPa

To assess the capabilities of the approach studied in this work and to evaluate the formability of the extruded WPC profile, a set of tests was conducted using extruded WPC. Formability can generally be understood as the ability of a material to undergo plastic deformation to a given shape without defects resulting from the characteristics of the material itself (Banabic *et al.* 2000). Tests were conducted using a hydraulic press with a set of punch and dies to assess the formability of the extruded WPC profile and the potential of the post-extrusion process in large-scale production.

The tool was specifically designed and manufactured for these tests and was mounted on a hydraulic C-frame press EPS40M made by Stenhøj A/S (Denmark) coupled with CA-1000 Connector Accessory made by National Instruments corporation (Austin Texas, USA) that uses VI Logger version 2.01 software made by National Instruments corporation (Austin Texas, USA) (Fig. 2). Data from the press tests were logged by computer and stored using Microsoft Excel 2007.

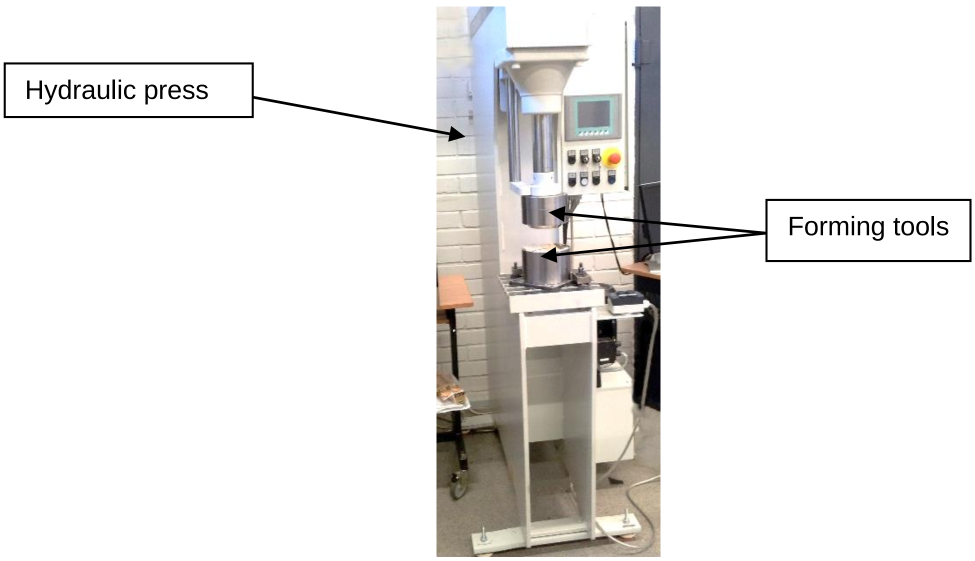

Fig. 1. Pressing tools mounted on the hydraulic press

A circular shape plate with a diameter of 148 mm was utilized in the forming tests. The uniform shape of the plate facilitates evaluation measurements of the outcome, simplifies assessment of the factors involved, and provides reliable baseline results that can be used in the study of more sophisticated and non-symmetrical shapes. The forming tools consisted of a male punch and female die (Fig. 2).

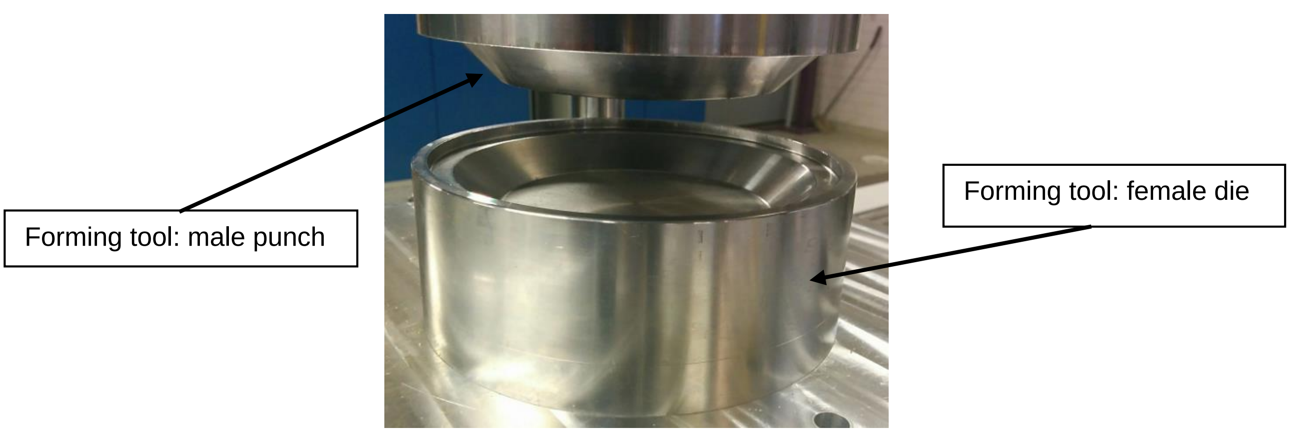

Fig. 2. Punch and die tools used for the forming test

The forming tool was subject to roundness tests to ensure its accuracy before the forming tests were performed. The roundness deviation of the forming tool was found to be 0.009 mm. The level of accuracy of the tool's roundness ensures that errors in the forming tool do not affect the forming test results.

The forming clearance of the punch for the conducted tests was set to 3 mm, with a cutting clearance of 0.08 mm and a punching force of 2 kN. The speed of the punch was 200 mm/s, die temperature was 20 °C, and the dwell time of press was 2 seconds.

Preliminary Forming Tests

Figure 3 presents photos of representative samples after the forming tests. Based on the material characteristics of WPC and in view of the forming process used, the temperature of the extruded sheet should be considered one of the key factors contributing to the success of the forming. Because cooling of the extruded profile begins immediately after the extrusion stage, tests were conducted at three temperatures to assist in the selection of a temperature range suitable for the forming process. The tests also provided an initial assessment of the formability of the material. Post-production can take place immediately after the extrusion, as an online process, or as a separate process after cooling of the extruded profile. The temperature of the material in forming may thus vary between room temperature and the extrusion temperature.

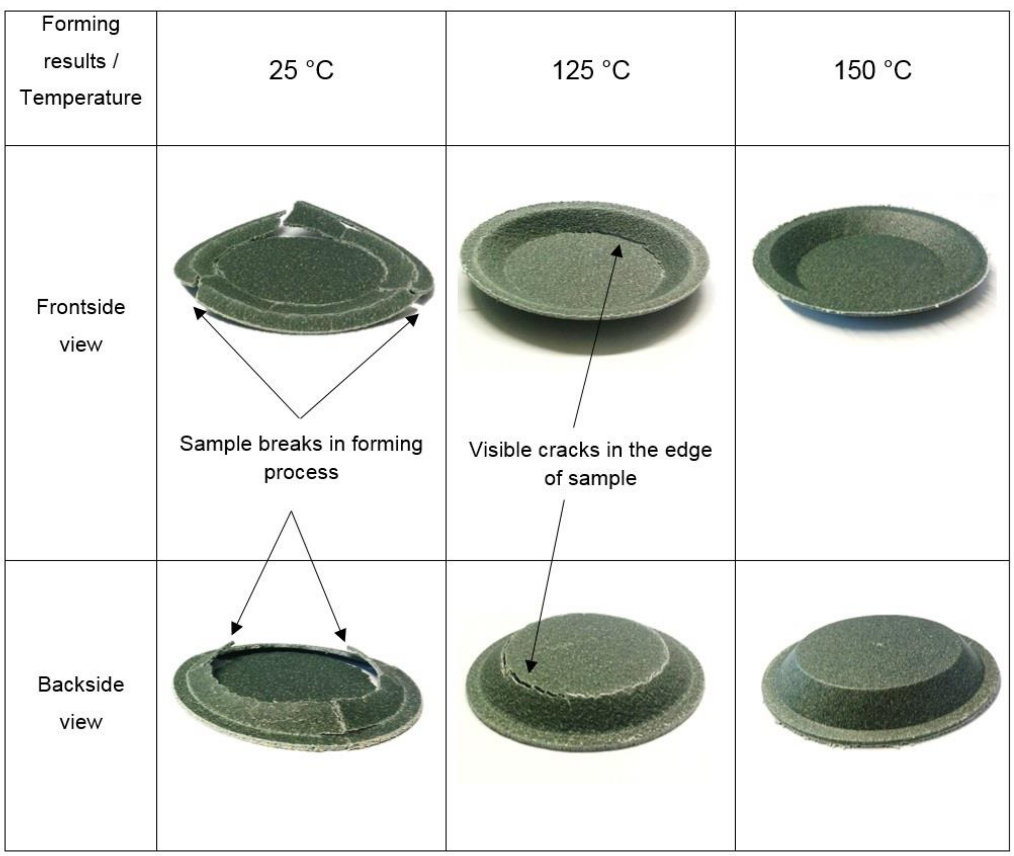

Fig. 3. Preliminary forming result. Increasing the temperature of the material before forming resulted in improvement of forming quality (Material breaks in forming at 25 °C, formability improves at 125 °C but the material cracks at angles, forming quality increases with no sign of cracking in 150 °C).

Three temperatures were chosen for the preliminary tests: the temperature of the profile immediately after extrusion, which is approximately 150 °C; a temperature close to the melting point temperature of the HDPE in the WPC material, 125 °C; and room temperature, which was considered to be 25 °C. Every test was repeated 15 times for each temperature such that WPC sheets were cut and transferred to a pre-heated oven AKZ 323 made by Whirlpool Corporation (Michigan, USA) for 15 min. They were then immediately transferred to the forming test.

In the preliminary forming tests, as shown in Fig. 3, the material formed at 25 °C was observed to break during the pressing stage. Pre-heating the material before pressing increased the formability, but even at 125 °C, acceptable results were not achieved, with obvious cracks found in the edges of the samples. Heating the material up to a temperature close to the extrusion temperature improved results such that no cracks were found on visual inspection and the samples appeared, visually, to be well formed.

Based on the preliminary test results, a temperature of 150 °C was selected for the forming tests. Thirty-five similar 200 mm*200 mm pieces of WPC sheet were cut and transferred to the pre-heated oven at 150 °C for 15 min and immediately, during the next step, transferred to the forming test. Figure 4 illustrates the outcome of a forming test with flashes still around the product.

In addition to the selection of optimal temperature, preliminary product quality was measured for the studied properties of two classes of product: Class A products, that is, products of quality suitable for use in a wide range of customer products; and Class B products, that is, products of quality suitable for use in bulk products.

Fig. 4. Sample plate before detaching of the product from the WPC sheet

Methods

To satisfy the demands of manufacturers, products need to be produced in a process that is not only stable but also repeatable. Furthermore, this process needs to operate with small variability in the final product, for example, with respect to the dimensions and other quality characteristics (Montgomery 2009). Normal distribution analysis was used to assess the stability of post-production processing of WPC and the repeatability of product forming.

To assess the formability of the extruded wood plastic composite sheets and the general feasibility of the process, a number of key parameters were selected for measurement. The measured parameters included deformation assessment, thickness variation, and surface roughness. Figure 5 presents the parameters evaluated in formability assessment.

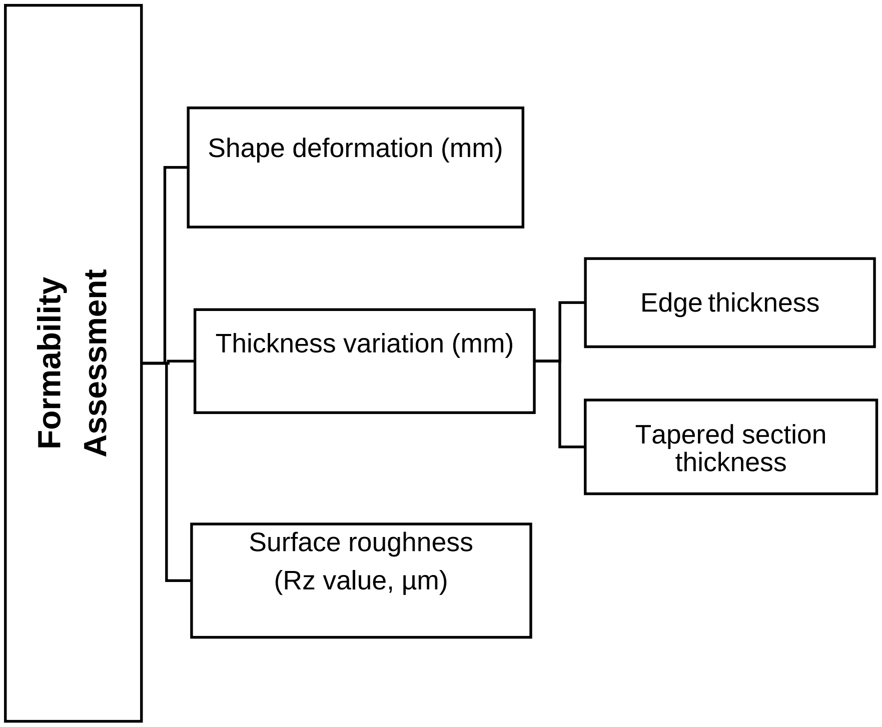

Fig. 5. Parameters evaluated in formability assessment

Shape deformation

Forming is done with a pressing method. Because the process temperature of the WPC sheet in forming is 150 °C, and HDPE is at the melting temperature, deformation problems are possible in the final product shape, especially after cooling. Thus, one set of measurements was conducted with samples cooled down to room temperature (25 °C). Two perpendicular diameters were compared, though in an ideal case the length of these two diameters should be equal. In the test, each plate was divided into four different quarters from point A to point D in such a way that the A-C direction was perpendicular to the B-D direction, as presented in Fig. 6.

Fig. 6. Sample #1 and divided sections A-D used for shape deformation and thickness variation measurement

All the plate quarters were named such that the A-C direction was the extrusion direction and as a result the predominant fiber direction in the plates. In an ideal case, A-C diameter length should be equal to the length in the B-D direction. In preliminary tests, it was found that too much dimensional variation in the sample could prevent successful stacking and packaging, and an acceptable dimensional range was thus set as 144 to 151 mm for Class A products and 143 to 153 mm for Class B products.

Thickness variation

One of the key parameters to be considered in the forming process is thickness variation in the product after pressing. Such data give information about the formability of the material as well as the repeatability of the production process. As the HDPE containing in studied WPC material is melted at the material temperature during the forming test, thickness variation was considered for edge thickness and tapered section thickness. The edge thickness is directly related to the pressing force and the tapered section thickness is affected by the force angle and flow of the semi crystalline material. In thickness measurement, each plate was divided into four quarters, A-D, as for the shape deformation test (Fig. 6). To ensure accurate results for comparison, each sample was located under the press in the same position and direction, and all four measured points experienced the same force.

In preliminary tests, it was found that areas less than 1.5 mm in thickness were easily deformed, bent and/or broken in handling, and thickness over 5 mm caused visible creep cracks in the longer side of corners. The acceptable thickness range for Class A products was set as 2 to 4.5 mm and for Class B products, 1.5 to 5 mm.

Surface roughness variation

Surface roughness indicates the suitability of the material and process for certain products or types of products; different products have different surface quality requirements. In addition to absolute surface roughness, variability in surface roughness and consistency of surface roughness are important measurements in assessing the formability of a product and the feasibility of a forming process. It should be noted that surface roughness is only one of several surface quality characteristics.

The preliminary forming tests at lower temperatures showed cracks and poor surface quality in the final product (Fig. 3). Samples produced at the higher temperature of 150 °C were found to be acceptable visually. It was decided based on visual and tactile inspection that product areas touched by customers should have less than 45 µm of surface roughness (Rz) for Class A products, to enable use in a wide range of products. This was set as the preliminary level of acceptance in the evaluation of roughness.

To measure the surface quality of the product more accurately, surface measurements were made with a hand-held surface roughness tester Innovatest TR-110 made by Innovatech Holding BV (Maastricht, Netherlands). Surface roughness was measured for a length of 2.5 mm of the surface of the sample. In the test, each sample was divided into four quarters and the device was positioned perpendicularly to each of the four directions of the plates, enabling four similar sections of each plate to be measured. Figure 7 presents a schematic view of the four different directions measured in each sample in the roughness measurement test.

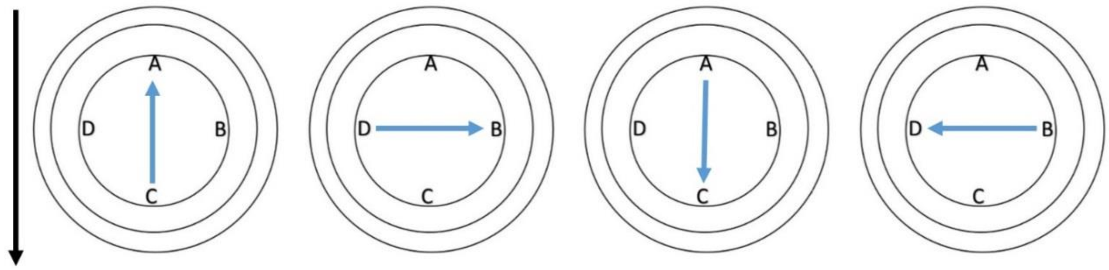

Fig. 7. Four directions measured in the surface roughness test. All samples were divided in four sections such that the A-C direction is the extrusion direction of the plates.

Statistical methods

In any production process, regardless of how the process is designed and maintained, some natural variability exists. Such variability, termed background noise, is the result of the combined effect of many small and unavoidable causes. Based on definitions in statistical quality control, this variability, following Walter A. Shewhart, is often called ‘a stable system of chance causes’. A process which is operating with only chance-cause variation is said to be in statistical control (Montgomery 2009).

This paper uses a statistical process control chart method to evaluate the feasibility of the studied process. The analysis is based on Phase 1 control chart results. In Phase 1, a set of process data are gathered and analyzed to determine if the process has been in control over the period of time when the data were collected. Moreover, it indicates whether reliable control limits can be found to observe future production. This process is typically the first action that is done when statistical control charts are applied to any process (Montgomery 2009). The control charts are plotted using 2 sigma level of confidence, which is 95.45% within two standard deviations of the mean value of the measurements taken. This accuracy can be considered sufficient for evaluation of the feasibility of the process. In addition to variability analysis, feasibility of the process was analyzed in terms of acceptability of samples based on a pre-determined classification of results in case of surface roughness, thickness and dimensional variation of the example plate products.

RESULTS AND DISCUSSION

Shape Deformation

Based on the results of the deformation test, material geometry variation was observed to be minimal. In terms of 2σ, the variance was about 1% or less in comparison to the mean value. It was observed that the product was nearly 2 mm bigger along the extrusion direction than in the perpendicular direction. This finding could be the result of the predominant fiber direction, which clearly affects the diameter of the product. This effect was also mentioned by Klyosov, who noted that thermal expansion is greatly affected by the direction of the wood fibers (Klyosov 2007). The variance in diameter could be the result of the distinct orientation dependent properties of WPCs.

The original tool diameter was 149.4 mm, and it was seen that the diameter of the plate in the A-C direction, which is along the extrusion direction, was close to the tool value. Low variance range in 2σ value indicates the capability of the post-production process to attain the desired form and geometry.

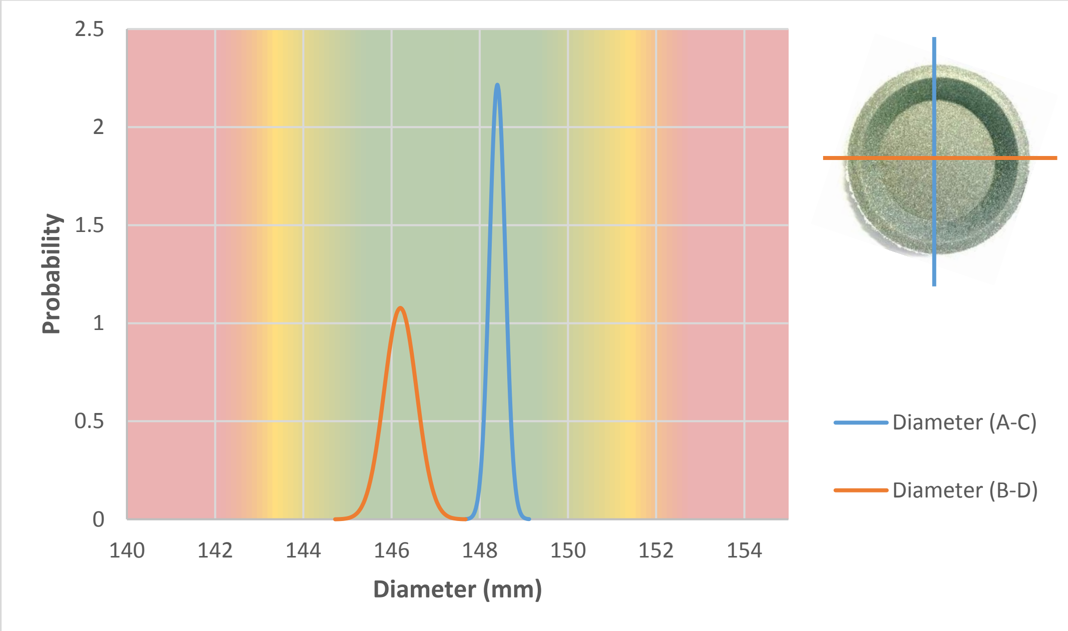

Fig. 8. Normal distribution diagram for deformation assessment. The A-C diameter, the predominant fiber direction based on extrusion direction, clearly longer than the B-D diameter. Color gradient in the background describes the preliminary level of acceptance of the product quality of the sample product, where green is Class A product, yellow is Class B product, and red is unacceptable product.

Both curves were observed to be in the range of preliminary acceptable levels based on the stackability of the samples, although the mean values were near the borders of the acceptable range.

Table 2. Quality Control Results of Categorized Shape Deformation Data for the Two Measured Diameters

	A-C Direction	B-D direction
Mean	148.4	146.2
Standard deviation σ	0.182	0.370
2σ variance range	148.04 – 148.76	145.46 – 146.94
2σ variance in comparison to mean value	0.53%	1.01%

It is known that at the high temperatures found in a hot-pressing process, degrading of mechanical properties takes place, of which bending strength is the most affected property (Winandy and Krzysik 2007). The effect of drying depends on the pulping process used. A typical phenomenon found in drying of kraft pulp fibers is hornification, which may lead to decreased strength properties of the fiber network. Hornification of kraft pulp is linked to lower content of lignin and hemicellulose (Göttsching and Pakarinen 2000). The dimensional stability of eucalyptus based WPC can be improved by treating the material with heat, which hydrolyzes the hemicellulose, which is the most hydrophilic component in wood fibers, and makes the matrix less hydrophilic. Better dimensional stability is a result of decreased swelling of fibers present in the composite material

(Ayrilmis *et al.* 2011). Improvement in the repeatability of the process is thus possible by adding more heat to the process.

Roughness

Roughness variation, $\underline{R}_z$, was measured and found to be similar in all measured points, namely in the range of 25.39 to 46.14 µm. The original roughness of the material, *i.e.* after extrusion and before forming, was between 50.8 to 113.2 µm, and the roughness of the press tools was measured to be 4.7 µm. The high variance range in the 2σ value (Table 3) indicates that the process in its current form is not in statistical control from the viewpoint of the surface quality of the final product. The variation of the surface roughness in the final product can be attributed to the considerable variation in the extruded material thickness, since the thicker parts of the sheet were formed better in comparison with thinner sections due to the uneven pressing force distribution. Measured normal curves were observed to be within acceptable Class A levels with a probability of 85%, and within Class B levels with a probability of 98%. Depending on the intended function of the formed product, this variation in surface roughness may be considered as acceptable for some bulk products but not for other more sophisticated products. In all the samples used in the forming test, surface quality improved after forming. This indicates that it is possible to regulate the surface roughness using an appropriate pressing force.

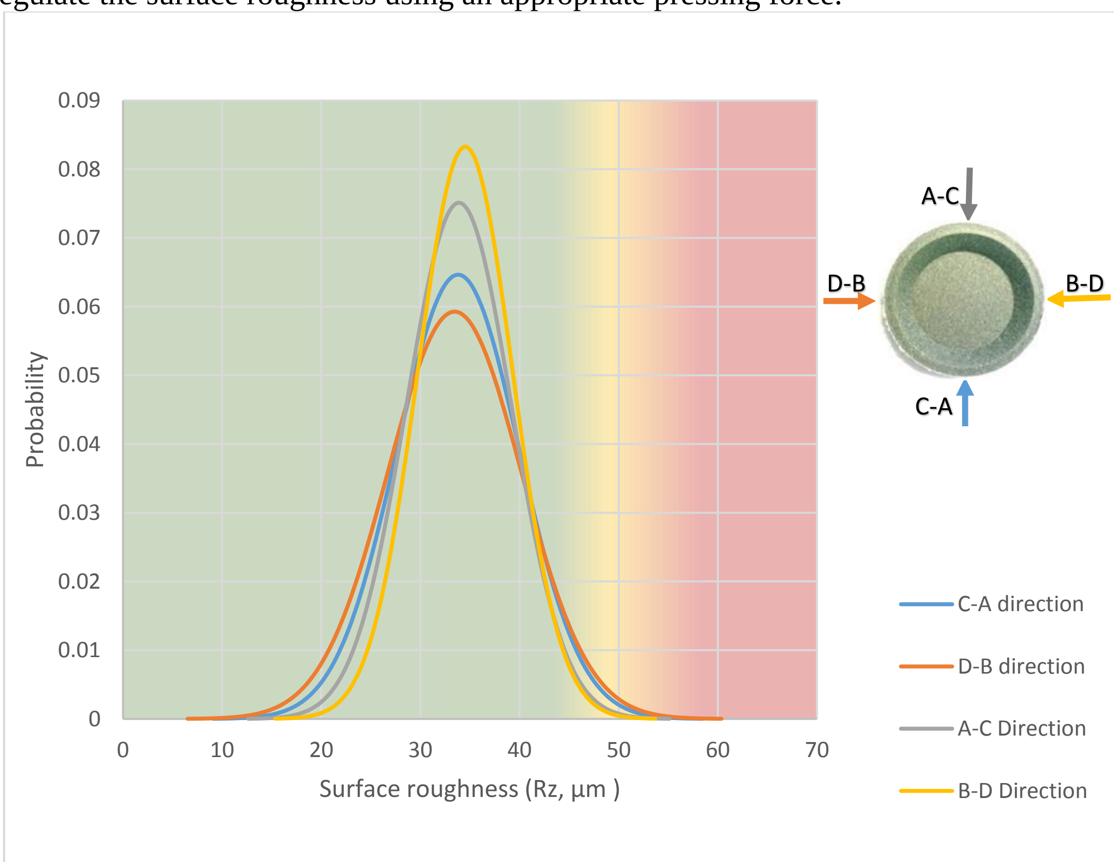

Fig. 9. Normal distribution diagram for surface roughness measurement based on four measured sections. Roughness variation in the A-C direction (extrusion direction) was less than in the B-D direction. Color gradient in the background describes the preliminary level of acceptance range based on visual and tactile inspection, where green is Class A product, yellow is Class B product, and red is unacceptable level.

Table 3. Quality Control Related Results of Categorized Surface Roughness Data for the Four Measured Sections

	C-A direction	D-B direction	A-C direction	B-D direction
Mean	33.8	33.4	33.9	34.5
Standard deviation σ	6.17	6.73	5,31	4,79
2σ variance range	21.46 – 46.14	19.94 – 46.86	23.28 – 44.52	24.92 – 44.8
2σ variance in comparison to mean value	73%	80.5%	62.6%	57.6%

Thickness Variation

Edge thickness

The edge thickness measurements, Table 4, had 2σ variance range for all four measured points, and maximum and minimum values ranged from 2.22 to 2.88 mm. A 2σ variance range in comparison with mean value indicates that the edge thickness of the press formed product was not highly repeatable and deviated by nearly 25 %. On the other hand, comparison of the thickness measurement results for the extruded WPC sheet before the forming process showed that thickness variation of the extruded sheet closely resembled the results after the forming process, *i.e.*, the post production process did not change the total variation. However, thickness variation of the original sheet directly influenced the thickness of the final product. The mean value of thickness for the four different quarters varied between 2.52 to 2.56 mm, indicating relatively similar thickness for each point. This result suggests that the force was distributed equally and the alignment of the forming tools was acceptable.

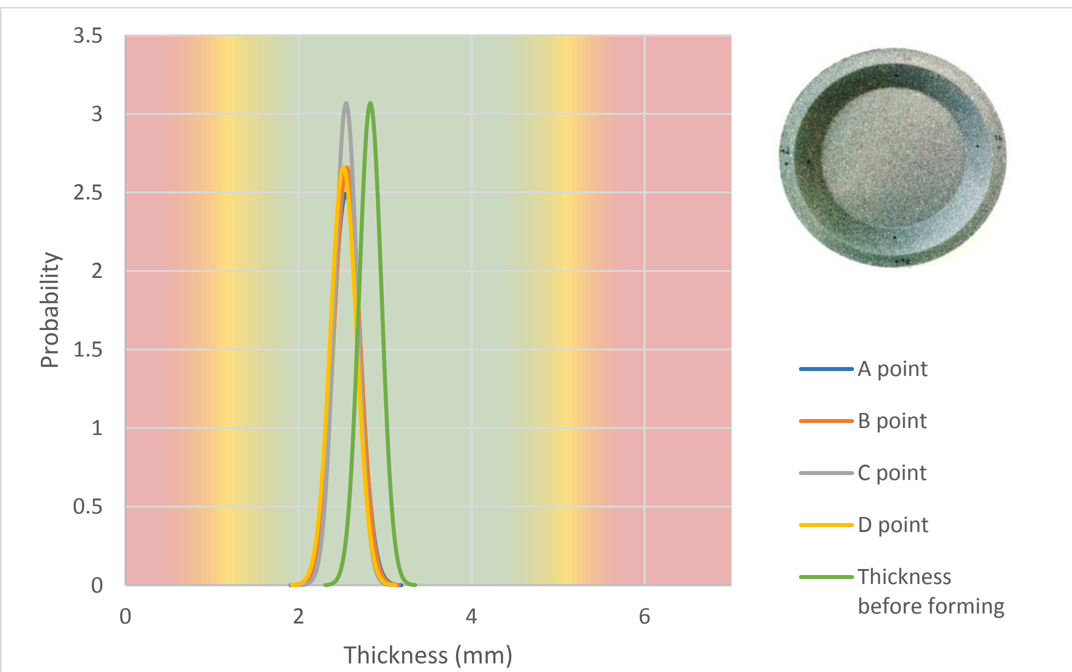

Fig. 10. Normal distribution diagram for edge thickness variation based on four measured points and the material characteristics of the original WPC sheets. Thickness variation for all four measured points is about the same and quite similar to thickness variation of the original material. Color gradient in the background describes the preliminary level of acceptance range based on durability and corner geometry, where green is Class A product, yellow is Class B product, and red is an unacceptable level.

Based on the preliminary durability and corner geometry assessment from thickness variation measurements, it was noted that both curves are well within the limits of acceptable ranges. The mean value of thickness of 2.85 mm in the extruded sheet before the post-production process decreased to 2.55 mm in the final samples. Based on the thickness measurements and the earlier surface roughness measurements, it can be seen that the thickness reduction happened only in thicker sections of the product. In an ideal situation, the amount of average thickness reduction should cover the whole range of thickness variation, which would make the surface roughness constant. Thus, the material should either have less thickness variation or the pressing temperature and force should be increased. Figure 10 shows normal distributions of the results of edge thickness measurements at points A to D and in the original material.

Table 4. Quality Control Related Results of Categorized Edge Thickness Variation Data for Four Measured Points

	Point A	Point B	Point C	Point D
Mean	2.55	2.56	2.55	2.52
Standard deviation σ	0.163	0.155	0.137	0.151
2σ variance range	2.22 – 2.88	2.25 – 2.87	2.28 – 2.82	2.22 – 2.82
2σ variance in comparison to mean value	25.8%	25.3%	24.3%	23.8%

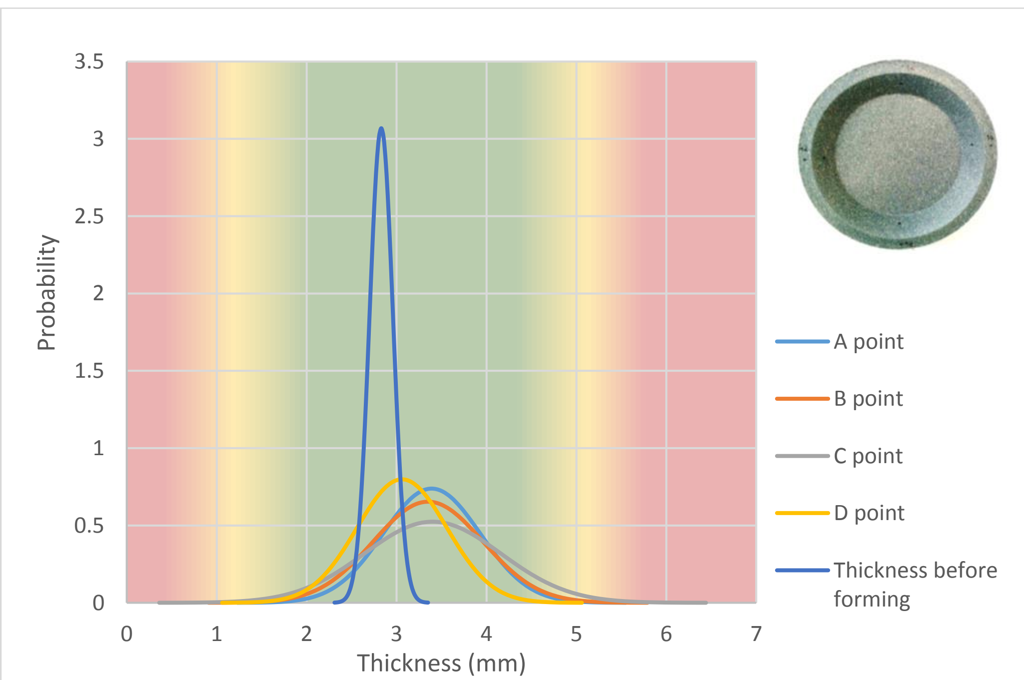

Fig. 11. Normal distribution diagram for thickness variation of the tapered section based on four measured points compared to thickness variation of the original sheet. Thickness variation in the original sheet is much lower than thickness variation in the tapered section. Color gradient in the background describes the preliminary level of acceptance range based on durability and corner geometry, where green is Class A product, yellow is Class B product, and red is an unacceptable level.

Thickness variation of the tapered section

The mean value of thickness for the four points in each quarter ranged from 3.06 to 3.40 mm. In the tapered side of the plate, thickness variation increased to 0.34 mm after the process in comparison to the original material thickness variation of 0.24 mm. Interestingly, the mean value of thickness in the tapered section was 3.30 mm, which is 0.45 mm more than the mean value of the original WPC sheet. The high variance range in the 2 σ value (Table 5) indicates that the process in its current form is not in statistical control for the tapered section thickness of the final product.

Table 5. Quality Control Related Results of Categorized Tapered Section Thickness Data for the Four Measured Points

	Point A	Point B	Point C	Point D
Mean	3.39	3.35	3.40	3.06
Standard deviation σ	0.541	0.616	0.766	0.505
2σ variance range	2.31 – 4.47	2.12 – 4.58	1.87 – 4.93	2.05 – 4.07
2σ variance in comparison to mean value	47.1%	73.4%	90%	66.0%

Based on the thickness measurement results, it is clear that overall thickness increased in the tapered section of the product but decreased in the external part. These observations can be attributed to the fact that the geometry of the forming tools was originally designed for only one material thickness, 2.8 mm, which was selected on the basis of average material thickness. In design of the forming tools, the physical characteristics of the WPC at 150 °C should be considered, as the material is semi-crystalline at such temperatures and may flow under the pressing force. The issue is illustrated in Fig. 12.

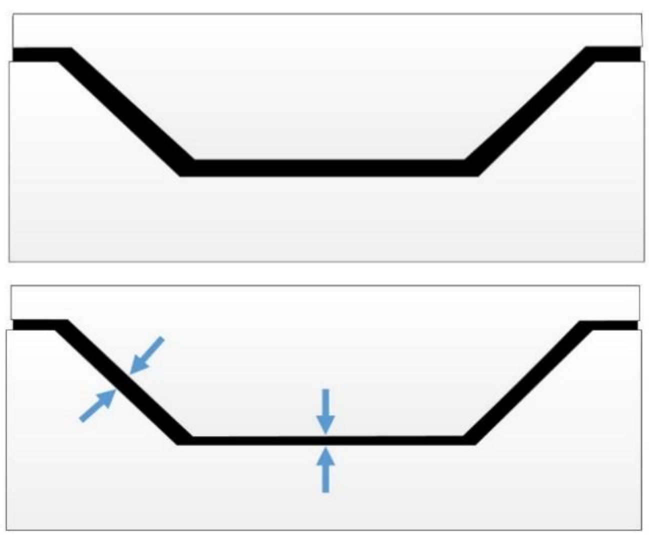

Fig. 12. Effects of tool forming tolerance on material thickness variation. The highlighted areas in the lower image present thickness variation of the material in the process caused by forming tools while the upper image shows constant thickness.

The image in the upper part of Fig. 12 shows the ideal case of material thickness. The lower part shows the case where the tapered section is thicker than the horizontal sections. To solve this problem for sophisticated designs and products, tools should either be designed in a way to accommodate this material variation or products should be designed in a way that some sections of products can be thicker.

As large variation was observed in some properties of the products, it is important to consider possible background factors. Variability of key quality parameters usually appears from three sources: unsuitably adjusted or controlled machines, operator errors, or defective raw material (Montgomery 2009).

In the case under study in this work, there were no signs of problems in the accuracy of the set up and alignment of the tools, and the machine operated correctly. The variability in the product was caused by large variation in material thickness. However, some variation should always be expected in WPC material, and therefore it is a question of to what extent the whole process, from material fabrication to post-production processing, could be tuned to reduce final product quality variation. With current material variation levels, it was observed that the product would not be suitable for Class A customer products requiring smooth surfaces with a probability of 15%. However, the variation in thickness and roughness caused by the post-process does not endanger the functioning or feasibility of the process; thus, the post-process could be considered under control.

Fine-tuning the process and its parameters, technically and economically, to ensure improved repeatability and reduced product variation, will permit use of the process in a wider range of applications, thus reducing landfill waste and contributing to greater sustainability. This sustainability factor is important in maintaining the viability of manufacturing industry in the context of ever-tightening environmental legislation.

CONCLUSIONS

1. Based on the results of preliminary forming tests it was found that in the temperature range of the extruder temperature, it is possible to produce potentially useful shapes *via* pressing method; the tests also clearly showed the importance of temperature in the forming process. Thus, to make such post-production processes possible, pre-heated WPC profiles need to be used or the process must be set up directly after the extrusion, as an online process. An online approach can save energy, time and production space and makes the process more eco-friendly and economical.
2. Based on the deformation test result, it was found that the predominant fiber orientation also affected the forming result. The product was nearly 1.3% bigger along the extrusion direction as a result of the effects of the direction of the wood fibers. This phenomena should be taken into consideration in press forming of the products and design of the proper production tools especially for complex shapes.
3. Forming test results indicated that the produced samples were accurate with respect to geometrical shape and deformation of the product after cooling. The 2σ variance in comparison with the mean value for the diameter was approximately 1%, which indicated that the process was repeatable when geometry was considered as a primary goal of the press forming process.

4. Surface roughness and thickness variation test results indicated that the process faces challenges in regard to the repeatability of these parameters. Thickness variation was found to be dependent on the original extruded WPC sheets, which suggests that improvements in repeatability results for surface quality and thickness variation may be possible by improving the quality of the extruded WPC sheets. Measurement results showed that variations in edge thickness and surface roughness decreased after the press forming.
5. In view of the material characteristics of heated WPC and the use of semi-molten material in press forming, material behavior under pressing forces needs to be considered during design of the forming tools. Modifications are required to decrease the thickness variation in angled sections of the product.

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