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Single-step manufacturing of curved polypropylene composites using a unique sheet consolidation method

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ABSTRACT

Many techniques have been developed over the past few decades to manufacture curved fibre reinforced thermoplastic composites. Long-fibre composite parts have been mostly manufactured by either compression moulding or thermoforming in two or more steps. No effort has been put into single-step manufacturing of long fibre curved thermoplastic composite parts. This work develops a manufacturing plan that has the ability to produce fairly strong curved thermoplastic composites in a single step. The production of composites according to this plan is expected to be significantly cheaper than the composites produced by compression moulding or thermoforming. In this research, curved composites were manufactured from flax reinforcements and polypropylene sheets using a unique manufacturing cycle, where the composites were formed and consolidated simultaneously. The optimum processing parameters and the fibre volume fraction were found to manufacture curved flax reinforced polypropylene composites with acceptable tensile and shear strengths. An experimental setup was used to monitor and record the applied vacuum pressure and temperature during the experiments. Shear and tensile strength of the manufactured composites was found. The consolidation quality of the manufactured composites was assessed by examining the composite specimens' cross-sections under an optical microscope. The results showed that the tensile and shear strengths of the manufactured composites were dependent on the fibre volume fraction, transverse permeability of the fibre reinforcement and also the magnitude and method of application of compaction pressure. There were optimum fibre volume fractions with respect to tensile and shear strengths for each of the three fibre reinforcements used in this research. The shear and tensile strengths of the composites produced in this research are comparable to compression moulded or thermoformed parts.

1. Introduction

The use of thermoplastic composites has gained popularity in the recent past, despite high temperature and compaction pressure requirements to manufacture these composites in the desired shape. These requirements tend to increase the cost of manufacture, and hence most of the intricately shaped composites are manufactured with thermoset resins or with thermoplastic granules or powder. A further challenge while manufacturing curved composites, is the proper physical placement of fibre and polymer layers in the mould so that the composite can be formed in the shape of the mould. Furthermore, the dimensional accuracy of the product is expected to decrease during the forming phase of the manufacture as the intricacy of the composite shape is increased.

Brecher et al., 2011 noted that thermoplastic composites have the potential to cope with the increasing demands in the modern automotive production. The use of high specific strength, continuous fibre-reinforced, thermoplastic composites in automobiles can reduce energy requirements and result in lower CO_2 emissions. Further, the superior damping and energy absorption behaviour of the thermoplastic matrix can also increase the driving comfort and the security of modern cars. Furthermore, the recyclability of thermoplastic composites is expected to improve the composite life cycle leading to reductions in material wastage.

Yin et al., 2013 found that the factors affecting the success of a thermoforming process are the blank size, the rheological properties of thermoplastics in the blank, and the fibre orientation in the blank. Rietman et al., 2011 established that for unidirectional (UD) fibre reinforced thermoplastic composites, the fibre-matrix-interaction plays an important role in the inter-ply behaviour. The inter-ply behaviour involves the interaction between different plies and the interaction of the outer plies with the forming tools. While the viscosity of the matrix plays a major role in the

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sliding behaviour, the lay-up of the composite and the local sliding direction are also of great importance. In complex geometries, the inter-ply behaviour and friction between tools and laminate may lead to folding (non-laminar bonding) that limits the formability and product performance. Further, the reliability of material parameters such as the bending behaviour of single and stacked plies at high temperatures is also of importance in the forming process.

To study the forming process analytically, different approaches have been attempted by researchers and validated through forming tests. Suresh and Senthil Kumar, 2012 conducted experimental and numerical studies to predict the optimum processing parameters needed to produce wrinkle free composites. Research in this field could be extended to the investigation of the effects of sheet shape, sheet size, friction, circumferential compression, sheet material selection and different weaving patterns on the formability of thermoplastic composite sheets. Tanaka et al., 2012 found that the defects in the formed curved structure were not due to shear deformation but due to the local shape change. Moreover, the maximum shear angle is effective for uniform deformation and not effective for the local change in the shape.

Haanappel et al., 2014 found that there is a need for a better bending characterisation test in order to predict wrinkling. Wrinkling is an obvious defect in curved composites; however, the number of wrinkles, their size and distribution depend on the architecture of the fibre reinforcement and also the properties of the polymer. In case of doubly-curved surfaces, wrinkle-free forming of a laminate having more than two unique fibre orientations must invoke inter-ply slippage and intra-ply deformations. Haanappel et al., 2012 also found that the doubly-curved surfaces are sensitive to wrinkling in case of UD composites compared to the woven counterparts. Results showed that there is a limiting shearing magnitude before wrinkling is initiated. Haanappel et al., 2014 also realized that the balance between the apparent intra-ply, frictional and bending rigidity determines whether in-plane or out-of-plane mechanisms dominate the laminate deformation process. Sachs et al., 2013 found that the material resistance against intra-ply shear or out-of-plane bending also determines the formability and may decisively influence the wrinkle formation. It was shown that unidirectional composites suffer more from wrinkle development, than their woven counterparts. A deformation mechanism that plays a major role in wrinkle development on a microscopic scale is inter-ply slip. The unidirectional (UD) material also exhibits the lowest amount of inter-ply slip on a macroscopic scale.

In the book "Composite sheet forming" edited by Bhattacharyya, three steps in the process of sheet consolidation were identified by Astrom (Aström, 1997) (in the chapter Thermoplastic composite sheet forming). These steps were prepreg lay-up, prepreg consolidation, and sheet forming. Consolidation or forming of composites under vacuum was not recommended because of the need for high labour intervention. In the chapter, Thermoforming of Continuous Fibre-Thermoplastic Composite Sheets, Friedrich et al., 1997 indicated that it is essential but difficult to determine the temperature range for forming the composites using stamp forming in particular. In the chapter, Rheology of Long Fibre-Reinforced Composites in Sheet Forming, Advani et al., 1997 stated that the nature of the matrix fluid, the geometry of the reinforcing particles, the concentration of the suspended particles and the shearing motion of the fluid between the particles define the viscosity of a filled suspension. It was declared that the most complicated form of flow of a matrix through fibres is when the continuous fibre layers are stacked and the matrix is flowing through a curved geometry. Hence, little work has been carried out to understand the simultaneous forming and consolidation of thermoplastic composites.

Burkhart and Cramer, 2005 demonstrated a method to produce hemispherical carbon fibre/Polyamide-6 domes. Later, Campbell and Cramer, 2008 described an initial investigation into the fabrication of a thermoplastic anti-ballistic infantry helmet. Sadighi et al., 2008 compared the experimental results of manufacturing hemispherical composites using Polypropylene (PP) and glass fibres with analytical results. In each of these three studies, a two-step process was used where the tailored blanks were first consolidated or softened/melted and then formed into the required hemispherical shape with a matched-die mould. The results of the study by Campbell and Cramer, 2008, indicated a potential for cycle time improvement using thermoplastics, but further work was suggested to improve heat transfer during material pre-heating prior to forming and to automate several process steps. Sadighi et al., 2008 mentioned that there is a trade-off between the parallel and perpendicular stacking reinforcing fibres. Whilst stacking in several directions increases laminate strength, the non-laminar polymer flow during the forming process leads to compressive strain at sides of the hemispherical part causing fibre buckles at both sides of the hemispherical part. Hence, an optimized stacking sequence was found.

The aim of this research is to develop a single step manufacturing technique to produce curved thermoplastic composites where the forming and consolidation take place simultaneously. To achieve this, the following actions are planned:

- Analysing the effect of different volume fractions on the forming (shape and dimensions) and consolidation (structural integrity) of the manufactured composites
- Determining a suitable temperature range for the manufacture curved flax-PP composites
- 1.0.0.1 Exploring a suitable vacuum compaction cycle for the manufacture and forming of curved flax-PP composites.

2. Materials and manufacturing

2.1. Materials

Flax fabrics of density 1.49 g/cm^3 were supplied by LIBECO (Belgium) which has since become LINEO (France). Unidirectional (310 g/m^2), fine twill (330 g/m^2) and coarse twill (565 g/m^2) were the three variants of flax reinforcements used. Polypropylene (Moplen-HP548S) of density 0.9 g/cm^3 was supplied by Field International (New Zealand) in the form of 0.365 mm sheets. The melt flow rate of the polypropylene (PP) used was measured as 7.43 g/10 min at 230 °C.

Degradation in terms of weight-loss and mechanical properties of natural fibres was observed at high temperatures by Van De Velde and Baetens, 2001. This degradation was minor under inert conditions compared to that in air. Pre-drying of flax fibres before composite production is advised because it removes most of the moisture, affecting the mechanical properties of the fibres positively. Degradation of pectins was observed to occur during exposure of flax fibres to 180 °C. Residual strains of approximately 52% and retained stresses of 66% after two hour exposure to 180 °C were measured. Composite production temperatures higher than 180 °C were suggested to be avoided. The working environment was proposed be as inert as possible and the exposure time should be less than an hour to minimise the damage to the fibres.

2.2. Compressibility of flax layers

High compressibility becomes a beneficial property for fibre reinforcements when the compaction pressures are higher than the atmospheric pressures. In this research, the maximum compaction pressure was atmospheric pressure so the range to which the fibre reinforcements could be compressed was limited.