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Design of Tooling System and Identifying Crucial Processing Parameters for NFPC Manufacturing in Automotive Applications

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Abstract: The aim of this study was to design a tooling system for manufacturing automotive components using a natural fiber polymer composite (NFPC) material. As a case study, an automotive battery cover was selected and a compression molding tool was designed, keeping in mind the need for the simplicity of the tool and ensuring the low cost of this process. However, since the original part was injection-molded with virgin polypropene, some vital changes made in the part and tool design process were documented as a guideline to show new designers how to approach the design of parts and tools using a natural fiber polymer composite material. Additionally, the challenges faced during the manufacturing of composite parts with the new tool were also documented and solutions to these challenges were suggested for large-scale production. Finally, compressive testing was performed to evaluate the performance of the structure of the designed part and to compare the recycled polymer with NFPC material. Both wood and palm fiber composite material perform better in compression testing compared to the recycled polymer material.

Keywords: natural fiber; recycled polymer; automotive; design methods; tooling system; processing parameters

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1. Introduction

Nowadays, polymer matrix composites are used extensively in the automotive industry due to their lightweight and superior properties. These polymer matrix composites are reinforced by either synthetic or natural fibers. Synthetic fibers such as glass and carbon fiber are widely used in manufacturing fiber-reinforced polymer composites for the automotive industry. However, these fibers have certain disadvantages, such as the high density of glass fiber; the high cost of carbon fiber; they are difficult to recycle, non-renewable, and non-biodegradable; and the high energy consumption in their production [1]. Due to these reasons, many car manufactures are shifting towards the use of natural fibers, such as plant fibers or mineral fibers, in producing components for their car models.

Natural fibers possess desirable properties, such as being low-cost, abundant, renewable, and biodegradable, as well as requiring less energy in their production. However, natural fibers also have several drawbacks, such as their high moisture content, low fire resistance, and weak interfacial adhesion with the polymer matrix in the composite [2,3]. The efficiency of the interfacial bonding of fibers and the polymer matrix in the composite determines its overall mechanical properties [4]. In a composite, fibers provide strength and stiffness, but they cannot withstand heavy loads directly, thus a polymer matrix's primary function is to aid in the transfer of stress [1]. Surface treatment methods have been reported to improve the interfacial adhesion between fibers and the polymer matrix. Hence, numerous studies [5–8] have been conducted on this issue in the past and an improvement in the mechanical properties of composites after the surface treatment of fibers has been reported. Ma et al. [6] observed that alkali treatment of bamboo fibers improves the adhesion between the fibers and acrylonitrile-butadiene-styrene (ABS) matrix, which resulted in a significant increase in impact strength of the composite. Similarly, Saidah et al. [7] observed an increase in tensile strength after alkali treatment of rice straw fiber-reinforced composites for varying fiber content compared to untreated fiber-reinforced composites. Kim et al. [8] observed significant improvements in tensile, flexural and impact strength of the wood fiber-reinforced polypropylene (PP) after chemical treatment of wood flour with various types of silane.

In automotive, natural fiber polymer composites (NFPCs) can be used as a substitute for both metal and polymer components. Currently, car manufacturers use NFPCs in both internal and external applications, such as door panels, luggage compartments, seat backrests, headliners, and door linings [9–13]. Natural fibers such as wood, flax, hemp, sisal, and kenaf are most commonly used in the automotive sector as reinforcing materials in polymer composites. Daimler uses flax, hemp, sisal, and coconut fibers in their A-, C-, E-, and S-class models [9]. Similarly, BMW uses flax and sisal in their 7-series model [13].

Previous studies have applied both synthetic fiber composites [14–18] and NFPCs [5,7,19–25] in various automotive applications. Saidah et al. [7] examined the effects of fiber loading and alkali treatment on a rice straw fiber-reinforced composite for an automotive bumper beam application. They concluded that alkali-treated rice fiber-reinforced composites with a 30% fiber loading possess superior mechanical properties compared to a standard bumper and can be a viable alternative to the existing material used. Nayak et al. [25] investigated the thermo-mechanical properties of Ceiba pentandra bark fiber/poly (vinyl) alcohol composites for dashboard and door panel applications. They found that 20 wt.% fiber content composites exhibited superior mechanical and thermal properties and were highly suitable in the fabrication of automotive dashboard and door panels. However, there are few under-the-bonnet applications for NFPCs in the automotive sector. This is mainly due to the harsh working environment of the bonnet area, which can negatively affect NFPC components due to their low fire resistance.

Epoxy, PP, ABS, polyamide, and polycarbonate are commonly used in polymer matrixes in NFPCs in the automotive sector. For example, a flax/PP composite was used to produce engine encapsulations for Mercedes-Benz Travego coaches and a flax-sisal/epoxy composite was used to produce the door panels of their E-class model [26]. Currently, virgin polymers are primarily used as polymer matrixes in NFPCs in automotive applications [5,7,25]. However, due to the sheer volume of polymers used in various components of automobiles, it is also possible to reuse some polymers extracted from automobiles after their end of life and reuse them in automotive in the form of NFPCs. These recycled polymers might have a slightly lower performance value in comparison with virgin polymers, but they are an easily available, cheap, and sustainable option and, more importantly, can be used to create viable matrixes for NFPCs.

The most common manufacturing process used for producing NFPCs is injection molding [8,27–29], compression molding [27,30–33], and resin transfer molding [34,35]. Compression molding is a high-volume production process used to manufacture composites for automotive components. In this process, the composite material is placed into the cavity of a fixed female tool and formed by applying pressure to the material with the help of a moving male tool. The material is cured utilizing pressure and heat and formed into the desired shape within the gap of male and female tools [36]. Overall, it is a low-cost, simple, and high-volume process that is suitable for manufacturing a variety of shapes. Due to the simplicity of the process, the tooling system for compression molding also costs less compared to injection molding [37]. Thereby, compression molding is a low-cost and viable process for manufacturing NFPCs composite for automotive applications.

It is important to study the role recycled polymers can play in the automotive industry and how car manufacturers can use these recycled polymers as composite materials for industrial-scale production. Thus, it is necessary to identify the key processing parameters that promote the use of recycled polymers in composite materials to be used as primary raw materials for manufacturing automotive parts. This also includes ensuring the low cost of the entire new part development process, especially in terms of the processing and tooling cost, because high costs will not promote the use of recycled polymers. Therefore, the aim of this article is to design a compression molding tooling system for NFPC component manufacturing and identify keys areas of improvement for future research work. Additionally, the crucial processing parameters required in the manufacturing of the component were also studied and documented. Finally, the part produced using the new tooling system was tested to determine its mechanical properties, and the challenges faced during the design phase were documented.

2. Materials and Design

The goal of the study is to develop a compression mold tooling system to manufacture an NFPC component. Therefore, for the purpose of the study, an automotive battery cover was taken into consideration and a compression molding tool was designed for the battery cover. Additionally, the processing parameters required for producing the component were identified and studied. This case study of an automotive battery car will help us to understand the key factors influencing the material, design, and process parameters when using NFPC material for the development of a new part. The methodology of the new part development is presented in Figure 1.

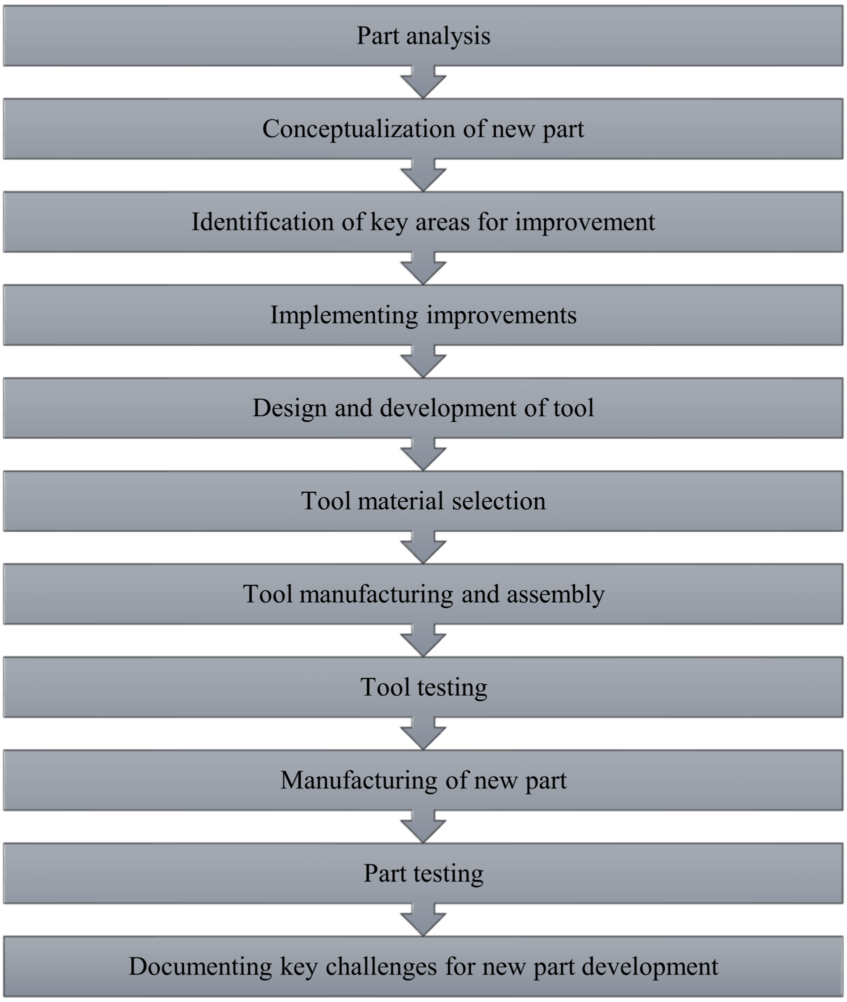

Figure 1. Methodology of the new part development.

Table 1 consists of all the key parameters that will be taken into consideration in developing the new part and tooling system for NFPC material. Previous studies related to the fabrication of NFPCs indicated that there were three crucial parameters in the compression molding process; these include temperature, holding time, and pressure [4,38,39]. However, considering the experimental setup of the study, few additional process parameters were added. From the design aspect, basic tool parameters such as tool clearance, draft angle, and parameters related to the part design were taken into consideration. Finally, the material parameters mainly involved the fiber content, melt flow index, and additives.

Table 1. Key parameters involved in the development of the new part for the automotive application.

Material	Design	Process
Fiber %	Height of the part	Compression time
Polymer %	Radius of edges	Pressure
Density	Thickness of part	Mold temperature
Melt flow index	Tool clearance	Material temperature
Additives	Draft angle	Material heating time

2.1. Design of Automotive Part and Tooling

In order to design a new tooling system, it is important to analyze the construction and manufacturing process of an existing polymeric automotive component and then design a similar part for the same purpose as that of the existing part, but which will use recycled polymer composite material. Furthermore, a change in the manufacturing material will not only result in the adaptation of the design of the part but will also require an adaptation in the manufacturing process, since the material, design, and process are interlinked and any change in one aspect may affect the other two.

Therefore, for the purpose of this study an automotive battery cover, as shown in Figure 2, was selected as a testing specimen. An automotive battery cover was used as a lid on top of the car battery alongside the battery casing to act as an extra measure of protection from any mishap related to the battery, such as leakage or preventing a dead short. The design of the battery casing and cover is mostly generic and is suitable to most of the batteries available on the market. The original part was manufactured from virgin PP using an injection molding process. The original part consisted of many hotspot points (shown in Figure 2) from which the material was filled into the cavity of the mold. These hotspot points improve the flowability of the material in the mold but, at the same time, increase the overall tooling cost and make the tool more complex. However, fiber-based composite materials are difficult to manufacture with the use of an injection molding process because the flow of the material inside the chamber will be greatly reduced due to the presence of fibers, while fibers can also cause the blocking of the orifice of the machine at the output end. Secondly, the high cost of the injection molding tooling system does not compliment the purpose of using recycled plastics and low-cost natural fibers from a cost saving point of view. Furthermore, compression molding is a common manufacturing process used to produce NFPC automotive parts and is highly compatible in producing large shapes [11]. Therefore, keeping such issues in mind, a compression molding process was selected for use in this study.

Additionally, many previous studies related to natural fiber polymer composites have found that the compression molding is a viable means to produce NFPC parts for automotive applications. Liu et al. [28] compared the samples produced by compression molding and injection molding and found out that the samples produced by the compression molding process exhibited superior mechanical properties. Tungjitpornkull and Sombatsompop [40] also found similar results; they observed that the samples produced by the compression molding process exhibited higher tensile strength than those produced by a twin-screw extrusion process. Bledzki and Faruk [29] compared the mechanical properties of wood fiber–PP composites produced using compression and injection molding processes. They found that compression-molded samples exhibited a better impact strength, while injection molding samples showed better tensile and flexural strength. Finally, Zampaloni et al. [32] stated that the optimal manufacturing process for producing NFPCs is compression molding.

Figure 2. Existing hotspot points in the virgin polypropylene (PP) automotive battery cover.

However, compression molding also has some limitations when used to manufacture fiber-based composite materials. One main issue is the height of the part, which in the case of the original part was relatively high; however, it is difficult to obtain such a height in compression molding when using a fiber-based material because the melt flow index of fiber-based composite materials is quite low compared with that of virgin polymer, which can easily be melted and compressed at a high pressure to fill the entire cavity of the mold. Similarly, it is also difficult to keep the thickness of the material constant because of the low mobility of fiber-based composite materials in the mold. It is possible that the thickness could be increased if additional material is present in the mold. Therefore, it is important that only a fixed amount of material is put in the mold for compression. Additionally, it is impossible to achieve complex features, such as those marked by red circles in Figure 3, using compression molding, because such features will obstruct the path movement of male tools and can also cause an increase in tooling costs if complex tooling is required.

Figure 3. Complex features in the existing component.

Therefore, during the re-design of this battery part, it is important that the existing design issues due to the limitation of the manufacturing process and material properties and behavior are taken into consideration in both the design and processing stages. Figure 4 shows a Solidworks representation of the battery cover design, considering all the existing issues. As shown in the figure, the height of the end of the cover was greatly reduced so that the composite material will flow smoothly up into the mold cavity. This is important from both a process and material point of view. If the height is too large, it is expected that the pressing machine will require a large amount force to push the material up into the cavity of the mold, and it is also possible that a greater amount of plasticizer will be required in composite preparation to improve the mobility of the material. Additionally, the side features were also removed and both sides were made uniform; we believe that this will not impact the function of the battery cover, whose main purpose is to provide extra measure of protection to the battery. However, practical applications are yet to be tested. The bottom thickness was kept uniform at 4 mm for the entire component.

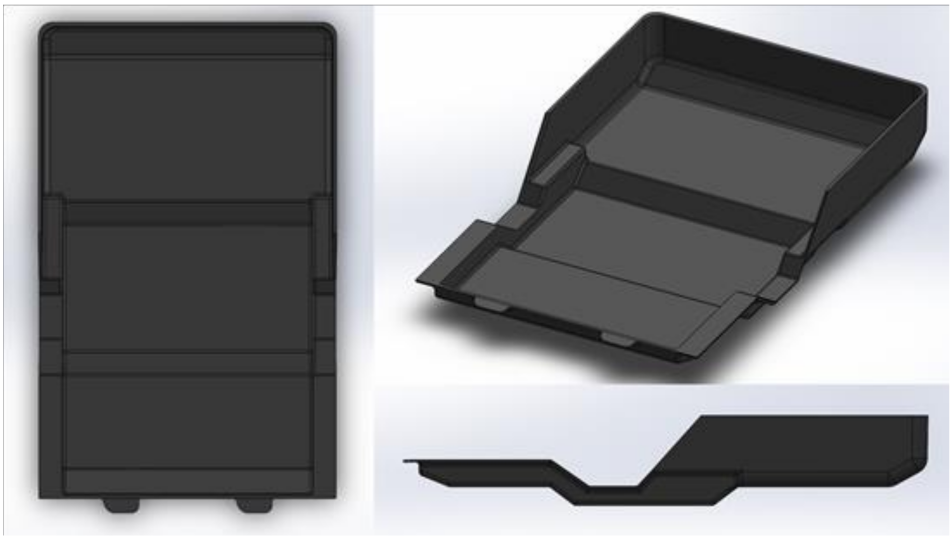

Figure 4. New automotive part design for the natural fiber polymer composite (NFPC) application.

As mentioned earlier, injection molding tools are generally complex and high cost, thus it does not make sense to have a costly tool, which would undermine the purpose of using recycled plastics and low-cost natural fibers. Therefore, it is important to keep the focus on developing a tool for the compression molding process that is simple and low cost. The mold (shown in Figure 5) for the newly designed part was produced at the Lappeenranta University of Technology (LUT) machining center using Toolox 34 engineering-grade steel. The mold design was a challenging aspect. The manufacturing of the mold required special long and small radius machine tooling because of the depth of the female mold. The long machining tool caused vibration during the machining process; therefore, a low feed rate was used, which resulted in longer cutting times. Furthermore, it was difficult to produce the inner radiuses of the female tool, especially for smaller dimensions. Some of angles of the designed parts were steep and not gradual.

Figure 5. Compressing molding tool manufacturing to produce natural fiber polymer composite (NFPC) components.

The cross-section view of the design compression molding tool in the assembly alongside the base plate by which it is connected to the compression molding machine is shown in Figure 6.

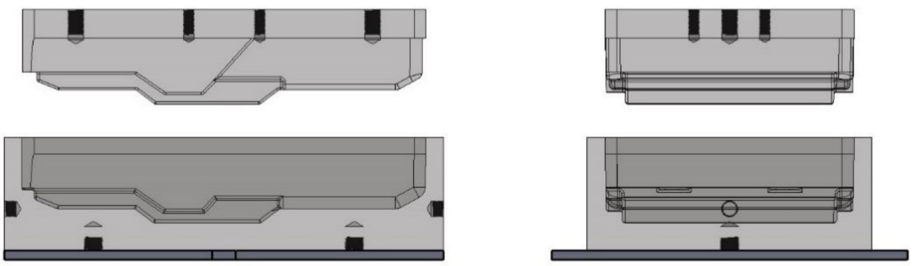

Figure 6. Representation of the compression molding tool in Solidworks.

2.2. Materials

The waste polymers, primarily consisting of ABS and other styrene-based polymers, such as ABS + polymethyl methacrylate (PMMA), ABS + polystyrene (PS), ABS + styrene acrylonitrile resin (SAN), ABS + acrylonitrile styrene acrylate (ASA), and ABS + acrylonitrile ethylene styrenes (AES), as shown in Figure 7, were supplied by Oili Jalonen Oy (Finland) and Majava Group Oy (Finland). These waste materials were extracted from automotive, motorbike, and truck polymer parts, such as motorbike frontal fairings, side fairings, tank covers, truck bumpers, car emergency triangle reflectors, and door panels. The waste automotive components were crushed into smaller granulates using a low-speed granulator

SHINI SG-1635N, as shown in Figure 7. The density and melt flow indexes of the recycled ABS mixture (R-ABSmix) were 1.032 g/cm^3 and 14.981 g/10 min, respectively. The wood fiber was obtained from Stora Enso Oy (Finland) and palmyra (bassine fiber) was obtained from Mirja Dahl Ky (Finland). The wood and palmyra fiber size used for the composite preparation were 20 mesh (0.85 mm). The density of the wood fiber and palmyra fiber was 0.457 g/cm^3 and 0.365 g/cm^3, respectively and the moisture content of the wood and palmyra fibers was 12% and 10%. STRUKTOL® TPW 113, a blend of complex modified fatty acid esters, was used as a lubricant, with a density of 1.005 g/cm^3 and a dropping point of 70–88 °C. EXACT elastomer was used as a plasticizer to improve the melt flow index of the composite material in the mold.

Figure 7. Illustration of the crushing process for the waste automotive components.

2.3. Agglomeration of Composites

The fiber material, R-ABSmix, lubricant, and plasticizer were compounded in a Plasmec COMBIMIX-RV/100/200/FV/W turbomixer with a cooler. Table 2 presents the composition of the prepared composite blends of R-ABSmix and natural fibers. Three different blends, including R-ABSmix, 10% wood fiber, and 10% palmyra fiber, were prepared for the experiment.

Table 2. Material composition of the recycled acrylonitrile-butadiene-styrene (R-ABS) and natural fiber composites.

Blend	Polymer	Fiber	Polymer (%)	Fiber (%)	Lubricant (%)	Plasticizer (%)
Blend 1	R-ABSmix	-	92	-	3	5
Blend 2	R-ABSmix	Wood	82	10	3	5
Blend 3	R-ABSmix	Palmyra	82	10	3	5

2.4. Compression Molding

All the blends were processed in a Stenhøj 400 kN compression molding machine. Six samples of each blend were produced for the experiment. Illustrations of the process setup and compression molding machine are shown in Figure 8. The process is a closed molding operation under high pressure. The blends were placed in the lower tool and spread evenly. Before the compression molding process, the blends were heated in a convection oven at 260 °C for 15 min and manually transferred to the compression molding tool. It is also important to note that even though the fiber degradation temperature was around 200 °C for most of the materials [38], it is important to ensure that the recycled polymer reaches its melting point. Therefore, considering the melting point of ABS and the possibilities of impurities in the recycled polymer mixture, a higher heating temperature was selected. However, the temperature of the composite material before compression was recorded using the Mastercool Infrared Thermometer OUTPUT < 1 mW AT 630~670 nm CLASS II and documented in Table 3. Additionally, both male and female tools were constantly heated using a hot air blower. The compression time was maintained at 120 s to achieve a perfect profile for the battery cover. Furthermore, the bottom position of the male tool was set up to achieve a final thickness of 4 mm for the component. Due to this, the pressure applied by the compression molding machine was the outcome of the entire process.

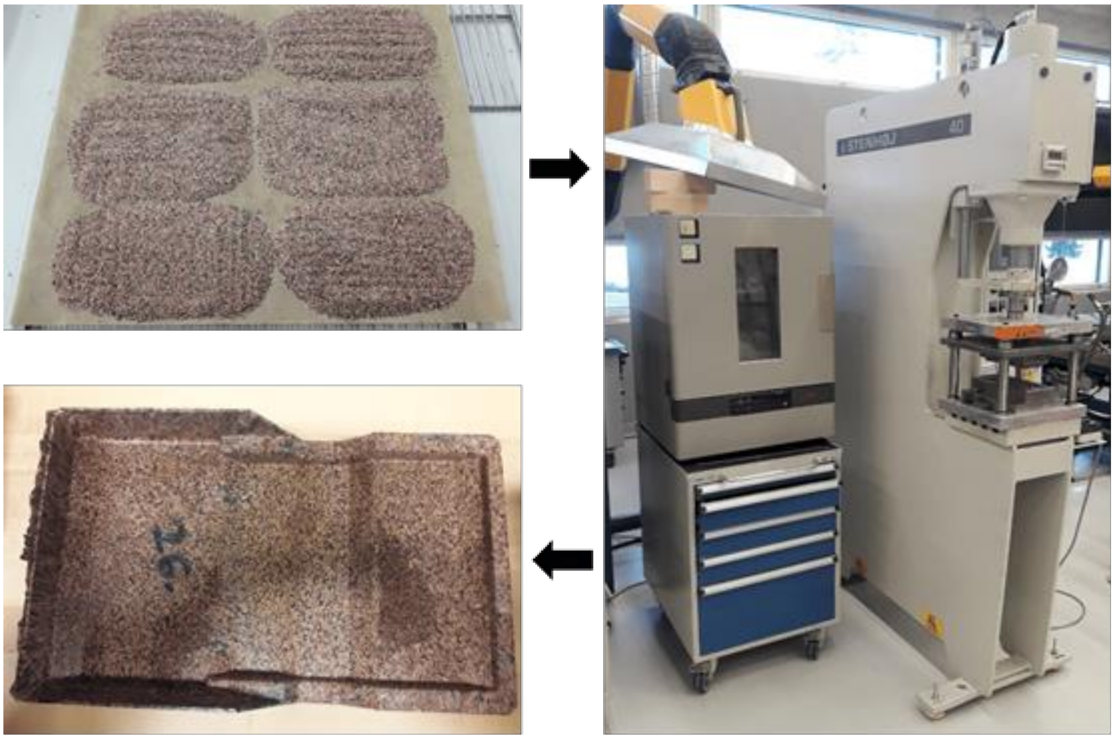

Figure 8. Compression molding setup and the production of the new automotive part.

Table 3. Processing parameters for the manufacturing of the new automotive parts.

Blend	Material Wt (gms)	Oven Temp (°C)	Material Temp (°C)	Heating Time (mins)	Female Tool Temp (°C)	Male Tool Temp (°C)	Compression Time (s)	Pressure (kN) *
Blend 1	400	260	205	15	71.5	62	120	392
Blend 2	400	260	204	15	68.5	60	120	392
Blend 3	400	260	202	15	70.5	63	120	395

* Pressure was measured as the outcome from the pressing machine.

The processing parameters used in the manufacturing of each composite component are described in Table 3.

2.5. Mechanical Testing

Since the primary function of an automotive battery cover is to act as protection for the top portion of a car battery, a basic compressive strength test was performed. The manufactured part from all three blends underwent compression testing to check the design and structural integrity of the part. The compression testing of the part was conducted in a universal testing machine (Zwick Roell Z020, Ulm, Germany) at a test speed of 50 mm/min with continuous loading. The experimental data were collected and processed automatically using the testXpert II software. Before testing, all the samples were cut into equal-height specimens, as shown in Figure 9.

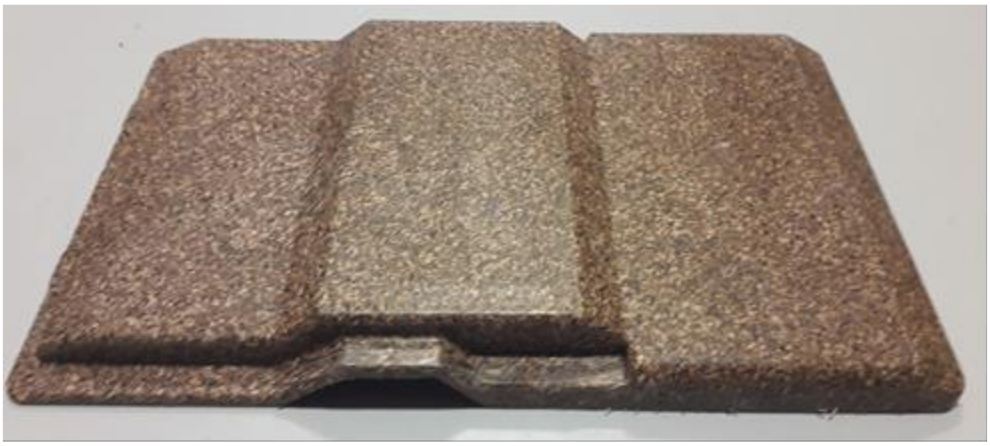

Figure 9. A specimen of wood fiber composite cut into shape for the compressive strength test.

3. Results and Discussion

3.1. Challenges in Design and Part Manufacturing

An initial design-related issue was the relatively small radius at the edges of the tool, which was kept at 3 mm during the tool design stage. The smaller radius made it difficult for the material in the mold to flow, and this was especially noticeable in the vertical sections of the mold. In some cases, the walls and the side horizontal surfaces of the final product did not come out of the mold filled. Usually, the melt flow index (MFI) of the polymer material decreases slightly after recycling [41], and it decreases further due to the presence of impurities in the recycled material. Moreover, adding fibers to the material to form the composite further decreases the flowability of the material in the mold. One solution to this issue is the better placement of material in the mold [42], as shown in Figure 10. It was observed that having an even distribution of the material in the mold results in the better flowability of the material compared to putting all the material in the center of the mold. Finally, to fully improve the flowability of both the polymer and composite material in the mold 5% *w/w* plasticizer was added to the material blends; this eased the flow of the material in the mold greatly. However, this led to a decrease in the overall mechanical properties of the material, because the addition of the plasticizer tends to make the material slightly softer. Finally, using a heavier pressing machine can also slightly improve the flowability, but, at the same time, this increases the cost of the machine drastically.

Another challenge observed with the designed tool involved the horizontal surfaces of the female tool, which, once filled with material and compressed by the male tool, acted as a counterforce to the force applied by the male tool. This primarily occurred due to the uneven levels of the horizontal surfaces. For instance, differences in height sometimes caused the material to be filled earlier at higher elevations and lock the tool in its place. This also affected the thickness of the material at the horizontal surfaces. If extra material is present in the mold, it can move towards these horizontal surfaces and accumulate there instead of coming out of the mold via runoff channels. The solution to such an issue is to have a multi-stage male tool, where the first part of the tool will come down slightly earlier than the main and lock all the horizontal surfaces at the desired height, apart from the main base of the female tool, where the working material is kept. An illustration of this is shown in Figure 11. However, such drastic and complex changes to the tool design which involve combining multiple tool pieces can significantly increase the tool cost. However, in our case, the focus was on developing a cheap and simple tooling system, and the results obtained from the designed tool were desirable for this study.

Figure 10. Evenly spread material placement, especially on the edges of the tool, provides optimal results.

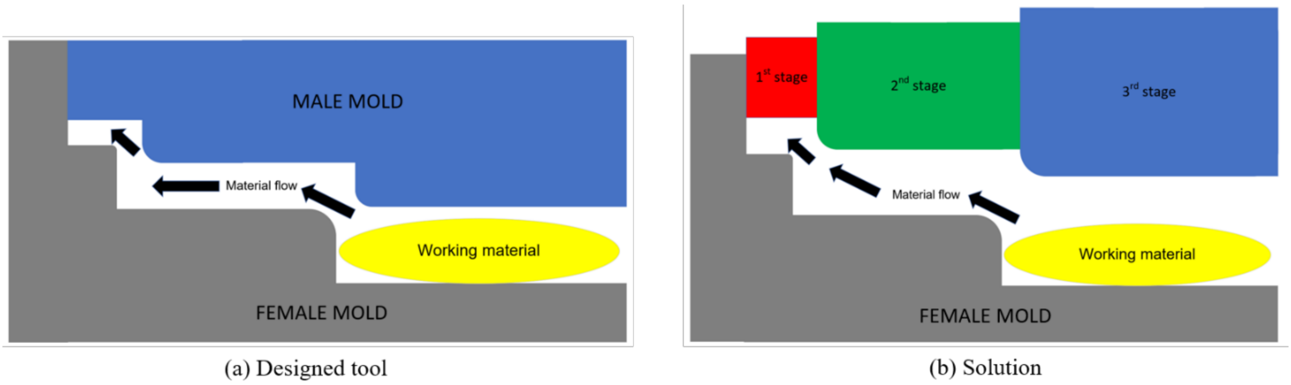

Figure 11. Illustration of (**a**) the designed tool for the production of the new automotive part and (**b**) the suggested change in the tooling system.

Then, it was found that the removal of the manufactured part from the tool was also difficult due to the depth of the female tool. This was more difficult when the part had just been pressed and was still hot, but it tended to come out easily once it had cooled. However, it can take several minutes for the material to cool down due to the high temperature of the material before putting it into the press with the heated tool. One solution we found was to add lubricant to the material blend, which greatly improved the removal process from the tool but, similarly to a plasticizer, had an adverse effect on the overall properties of the final product. Finally, another solution is to add an ejector pin to the base of the female tool as shown in Figure 12, which was proposed as a further modification for future testing [42].

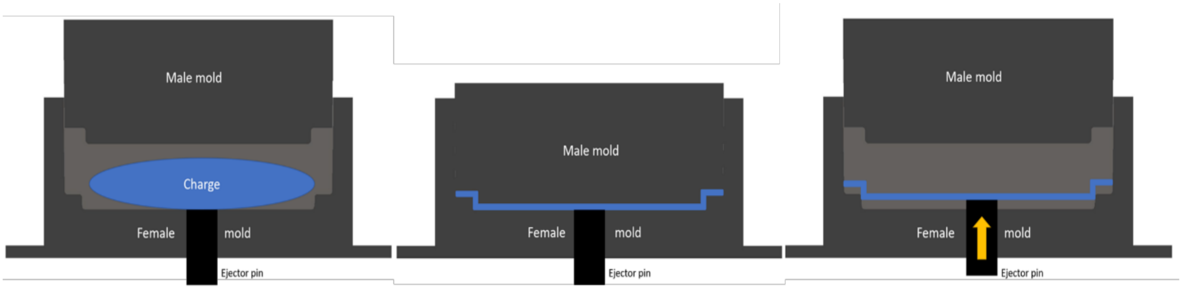

Figure 12. Proposed ejector pin for the new tooling system.

The next challenge was with the temperature difference between the heated material and the cold tool. Initial experiments were performed with the tools at room temperature; however, the results were not acceptable, since the manufactured product did not come out filled from the mold. Such a large and sudden temperature difference can affect the mechanical properties of the product and the flowability of the material in the mold. Finally, it was decided to manually maintain the mold temperature between 60 and 70 °C using a hot air blower. One easy solution for this problem is to add a heating coil to the female tool as shown in Figure 13 and use an induction process. This can make the tool more complex increase the tooling cost but can entirely replace the convection oven heating process. Syahirah et al. [43] designed and developed a heating system compression molding process and selected induction heating as the best heating method for the pressing process.

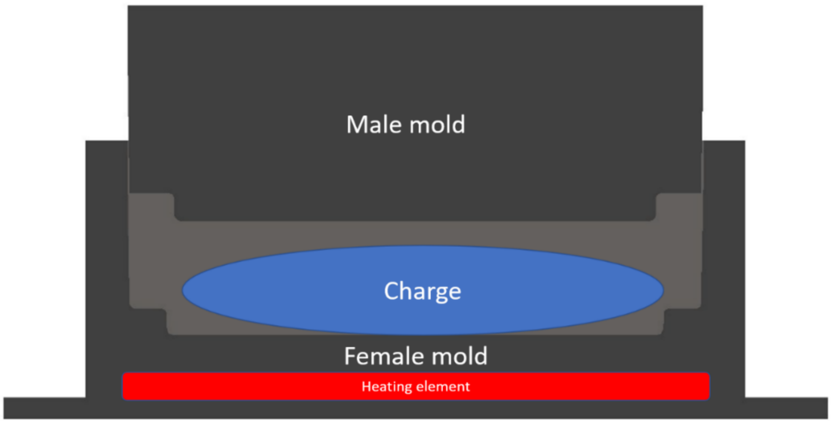

Figure 13. Proposed heating element for the new tooling system.

Numerous studies [4,33,39,44] have reported the preparation of NFPC specimens through the use of a compression molding process with an inbuilt heating system in the mold and analyzed the influence of the mold temperature on the mechanical properties. Yallew et al. [4] studied the effects of mold temperature on the tensile properties of fiber-reinforced PP composites. They found out that at 175 °C temperature and 1 MPa pressure all three fiber-reinforced PP composite types exhibit the highest tensile strength value. Takemura and Minekage [33] used heating plates in both male and female tools and then compared the effect of varying molding temperature on the tensile properties of hemp reinforced composite and jute reinforced composites. Although most of these studies used a mold temperature between 165 and 195 °C, most focused on polypropylene (PP) or high-density polyethylene (HDPE), which have relatively lower melting points. Since ABS melts between 200 and 220 °C, it is important to use a mold temperature in that range. For the experiment, we found that heating with hot air blowers produced acceptable results, but for full-scale manufacturing a proper heating system is required.

The last challenge was related to the handling of the heated material, since all the handling was conducted by hand using protective gears. However, implementing an automated system with conveyors can ease the handling of the material, speed up the overall process, and avoid any unnecessary injuries to the operator. This is especially important in this case because the oven, material, and the mold were all relatively hot. Therefore, for the purposes of our test, the setup can be viable, but for large-scale production a conveyor system would be preferable.

3.2. Mechanical Testing

The result of the compression testing of 6 samples of blend 1 (R-ABSmix) is shown in Figure 14. The maximum load required for breaking the parts was found to be between 1400 and 2100 N, with an average load of 1693 N and an average deformation of 14.38 mm. The average elasticity value for all the samples of blend 1 was observed to be 1568.68 MPa.

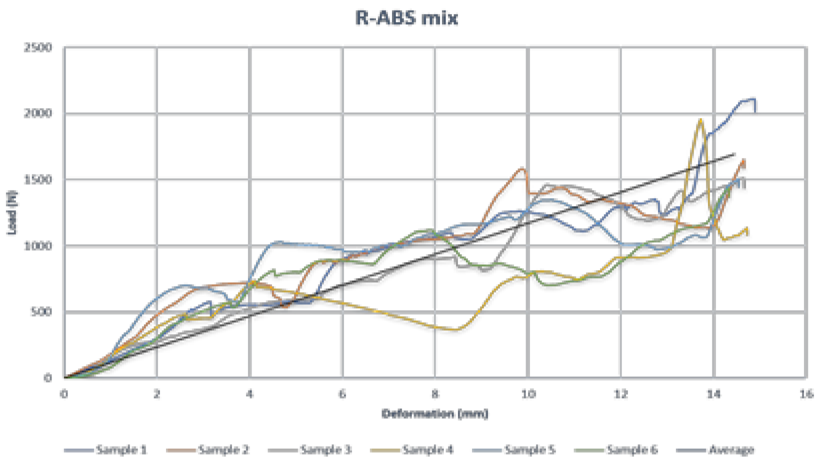

Figure 14. Compression testing results of the R-ABS mix blend.

The results of the compression testing of 5 samples (one sample was damaged during the handling phase) of blend 2 (10% wood) and 6 samples of blend 3 (10% palmyra) are shown in Figure 15a,b, respectively. For the wood fiber composite, the maximum load required for breaking the parts was found to be between 2350 and 3600 N, with an average load of 2690 N and an average deformation of 10.15 mm. The average elasticity value for all the samples of blend 2 was observed to be 3156.43 MPa. Meanwhile, for the palmyra fiber composite, the maximum load required for breaking the parts was found to be between 1450 and 2400 N, with an average maximum load of 1802 N and an average deformation of 12.97 mm. The average elasticity value for all the samples of blend 3 was observed to be 2032.95 MPa.

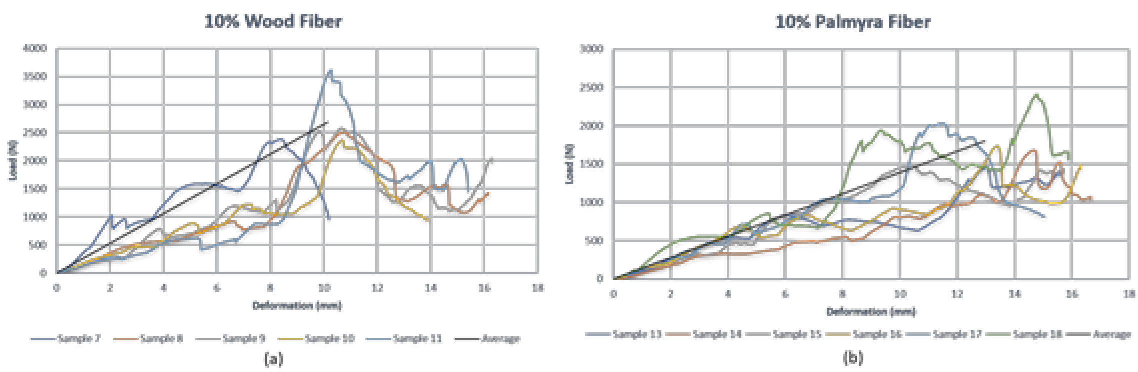

Figure 15. Compression testing results for (**a**) wood and (**b**) palmyra fiber composite blends.

It is evident that the addition of natural fibers had a positive effect on the compressive properties of the composite material. Numerous studies in the past have also observed similar results [27,30,31,45,46], where the addition of natural fibers to the polymer matrix increased the compressive strength of the composite. Kumar and Srivastava [45] observed that the addition of jute fibers to epoxy resin increases the compressive strength of the composite in comparison to the epoxy material. They attributed this increase to the interfacial bonding between the fibers and the polymer matrix. Similarly, Singha and Rana [27] found that composites reinforced with either 10% wt. raw agave fiber or MMA-grafted agave fibers exhibited high compressive strength values compared to virgin polystyrene. They also observed that irrespective of using short or long fibers, the compressive strength value was higher for the composite material. Also, Singha and Thakur [30] observed that the compressive strength of urea-formaldehyde resin increased when reinforced with natural fibers. They found that particle reinforcement exhibits better compressive strength values than short or long fiber reinforcement.

However, in the case of the palmyra fiber composite, the increase in compressive strength was less than the increase in the wood fiber compressive strength. It was assumed that the interaction between the palmyra fibers and polymer matrix was relatively weak compared to the interaction between the wood fibers and polymer matrix, indicating that wood fibers have more affinity for polymer interaction than palmyra fibers.

Finally, a statistical analysis was performed in Daniel's XL Toolbox Excel software, using the one-way analysis of variance (ANOVA) Bonferroni–Holm post hoc testing algorithm to verify the significance of the variations in the results. Table 4 displays the average values of elasticity, load, and deformation for all three blends. It was observed that the wood fiber composite exhibited significant changes, while the palmyra fiber composite exhibited non-significant changes in comparison with the R-ABSmix material for all the values.

Table 4. Compressive testing results of all three blends; ^{s} and ^{ns} denote statistically significant and not statistically significant changes at the 95% confidence level.

	Elastic Modulus (MPa)	Load (N)	Deformation (mm)
Blend 1	1568.68	1692.70	14.45
Blend 2	3156.43 ^{s}	2690.36 ^{s}	10.15 ^{s}
Blend 3	2032.95 ^{ns}	1802.66 ^{ns}	12.97 ^{ns}

4. Conclusions

This study focused on designing a tooling system for the use of NFPCs in automotive applications and identifying the crucial parameters involved in the design and processing of the part. For the purposes of the study, an automotive car battery cover was selected as a case study, because little focus has been given to NFPC applications in under-the-bonnet applications. The design of the new part and the tool has been explained in detail, considering various elements during the design and manufacturing phase when working with NFPC as a material. Additionally, all the challenges faced relating to the design, material, and processing of the part were also documented, which in turn can aid designers in implementing solutions for these challenges in their work.

The challenges faced during the study related to the design, material, and processing. They included the low melt flow index of the material due to the introduction of fibers, the small radiuses at the edges of the tool, the horizontal surfaces of the tool, the lack of an ejector pin at the bottom of the tool, and the lack of a heating element in the tool. However, it is also important to understand that implementing certain features to overcome some of these challenges will drastically increase the cost of the product. Therefore, due to the scale of this experiment, such features were not pursued but could be implemented during mass-scale production. The primary aim of this study was to evaluate the possibility of using NFPCs from recycled polymers in automotive applications and identifying key areas for improvement.

The compressive testing of the NFPCs and recycled ABS displayed that both wood and palmyra fiber composites possess a high compressive strength and exhibit low deformation values. Such results clearly indicate that the composite materials exhibit a higher compressive strength than recycled ABS due to their high elasticity/stiffness and the interfacial bonding between the fiber and matrix, which aids in stress transfer. This further increases the potential of NFPCs from recycled polymers to be used as construction materials in automotive part manufacturing. In future research, the focus should be on the cost and lifecycle analysis of the case study component and material to understand the economic and environmental aspects related to use of recycled materials.

Finally, it is important to understand that the purpose of this study was to explore the possibility of using recycled polymers from automotives combined with natural fibers and provide a guideline on how such material can be utilized again in the automotive industry. We were able to produce an automotive battery cover with desirable properties using a simple tooling system and manufacturing process. However, we made some changes to the original design of the automotive battery cover in order to fulfil the goal of the study, which was to use recycled material to produce a low-cost and simple part. Hopefully, this will help future researchers to focus their attention on these materials and promote their usage in both experimental and practical applications.

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References

1. Chauhan, V.; Kärki, T.; Varis, J. Review of natural fiber-reinforced engineering plastic composites, their applications in the transportation sector and processing techniques. *J. Thermoplast. Compos. Mater.* **2019**, 0892705719889095. [CrossRef]
2. Khan, T.; Bin, M.H.S.T.; Ariffin, A.H. The challenges of natural fiber in manufacturing, material selection, and technology application: A review. *J. Reinf. Plast. Compos.* **2018**, *37*, 770–779. [CrossRef]
3. Rohit, K.; Dixit, S. A review—Uture aspect of natural fiber reinforced composite. *Polym. Renew. Resour.* **2016**, *7*, 43–60. [CrossRef]
4. Yallew, T.B.; Kassegn, E.; Aregawi, S.; Gebresias, A. Study on effect of process parameters on tensile properties of compression molded natural fiber reinforced polymer composites. *SN Appl. Sci.* **2020**, *2*, 338. [CrossRef]
5. Marichelvam, M.K.; Manimaran, P.; Verma, A.; Sanjay, M.R.; Siengchin, S.; Kandakodeeswaran, K.; Geetha, M. A novel palm sheath and sugarcane bagasse fiber based hybrid composites for automotive applications: An experimental approach. *Polym. Compos.* **2021**, *42*, 512–521. [CrossRef]
6. Ma, L.; He, H.; Jiang, C.; Zhou, L.; Luo, Y.; Jia, D. Effect of Alkali Treatment on Structure and Mechanical Properties of Acrylonitrile-Butadiene-Styrene/Bamboo Fiber Composites. *J. Macromol. Sci. Part B Phys.* **2012**, *51*, 2232–2244. [CrossRef]
7. Saidah, A.; Susilowati, S.E.; Nofendri, Y. Effect of Fiber Loading and Alkali Treatment on Rice Straw Fiber Reinforced Composite for Automotive Bumper Beam Application. *Int. J. Adv. Sci. Eng. Inf. Technol.* **2019**, *9*, 1865–1870. [CrossRef]
8. Kim, T.-W.; Lee, S.-Y.; Chun, S.-J.; Doh, G.-H.; Paik, K.-H. Effect of silane coupling on the fundamental properties of wood flour reinforced polypropylene composites. *J. Compos. Mater.* **2011**, *45*, 1595–1605. [CrossRef]
9. Zhao, D.; Zhou, Z. *Applications of Lightweight Composites in Automotive Industries*; Yang, Y., Xu, H., Yu, X., Eds.; American Chemical Society: Washington, DC, USA, 2014; pp. 143–158. [CrossRef]
10. Norhidayah, M.; Hambali, A.A.; Yaakob, M.Y.B.; Zolkarnain, M.; Taufik; Saifuddin, H. A review of current development in natural fiber composites in automotive applications. *Appl. Mech. Mater.* **2014**, *564*, 3–7. [CrossRef]
11. Holbery, J.; Houston, D. Natural-fiber-reinforced polymer composites in automotive applications. *J. Miner. Met. Mater. Soc.* **2006**, *58*, 80–86. [CrossRef]
12. Ashori, A. Wood-plastic composites as promising green-composites for automotive industries! *Bioresour. Technol.* **2008**, *99*, 4661–4667. [CrossRef]
13. Mohammed, L.; Ansari, M.N.M.; Pua, G.; Jawaid, M.; Islam, S. A Review on Natural Fiber Reinforced Polymer Composite and Its Applications. *Int. J. Polym. Sci.* **2015**, *2015*. [CrossRef]
14. Ning, H.; Vaidya, U.; Janowski, G.M.; Husman, G. Design, manufacture and analysis of a thermoplastic composite frame structure for mass transit. *Compos. Struct.* **2007**, *80*, 105–116. [CrossRef]

15. Ning, H.; Pillay, S.; Vaidya, U.K. Design and development of thermoplastic composite roof door for mass transit bus. *Mater. Eng.* **2009**, *30*, 983–991. [CrossRef]
16. Ning, H.; Janowski, G.M.; Vaidya, U.K.; Husman, G. Thermoplastic sandwich structure design and manufacturing for the body panel of mass transit vehicle. *Compos. Struct.* **2007**, *80*, 82–91. [CrossRef]
17. Bartus, S.D.; Vaidya, U.K.; Ulven, C.A. Design and Development of a Long Fiber Thermoplastic Bus Seat. *J. Thermoplast. Compos. Mater.* **2006**, *19*, 131–154. [CrossRef]
18. Thattaiparthasarathy, K.B.; Pillay, S.; Ning, H.; Vaidya, U.K. Process simulation, design and manufacturing of a long fiber thermoplastic composite for mass transit application. *Compos. Part A Appl. Sci. Manuf.* **2008**, *39*, 1512–1521. [CrossRef]
19. Rosli, M.; Jamalludin, M.R.; Khor, C.Y.; Ishak, M.I.; Jahidi, H.; Wasir, N.Y.; Faizal, W.M.; Draman, W.N.A.W.; Lailina, N.; Ismail, R.I. Analytical Hierarchy Process for Natural Fiber Composites Automotive Armrest Thermoset Matrix Selection. In *MATEC Web of Conferences*; EDP Sciences: Paris, France, 2017. [CrossRef]
20. Pervaiz, M.; Sain, M.M. Sheet-Molded Polyolefin Natural Fiber Composites for Automotive Applications. *Macromol. Mater. Eng.* **2003**, *288*, 553–557. [CrossRef]
21. Paiva, A.F.; Camara, J.J. Alternative composite material for replacement of fiberglass laminates used in the manufacture of car body vehicle prototypes. *SAE Tech. Pap.* **2011**. [CrossRef]
22. Alves, C.; Ferrão, P.; Silva, A.; Reis, L.; Freitas, M.; Rodrigues, L.; Alves, D. Ecodesign of automotive components making use of natural jute fiber composites. *J. Clean. Prod.* **2010**, *18*, 313–327. [CrossRef]
23. Mansor, M.; Sapuan, S.; Zainudin, E.; Nuraini, A.; Hambali, A. Hybrid natural and glass fibers reinforced polymer composites material selection using Analytical Hierarchy Process for automotive brake lever design. *Mater. Des.* **2013**, *51*, 484–492. [CrossRef]
24. Dahlke, B.; Larbig, H.; Scherzer, H.D.; Poltrock, R. Natural Fiber Reinforced Foams Based on Renewable Resources for Automotive Interior Applications. *J. Cell. Plast.* **1998**, *34*, 361–379. [CrossRef]
25. Nayak, S.; Khuntia, S.K.; Mohanty, S.D.; Mohapatra, J. Investigation and Fabrication of Thermo-mechanical Properties of Ceiba Pentandra Bark Fiber/Poly (Vinyl) Alcohol Composites for Automobile Dash Board and Door Panel Applications. *J. Nat. Fibers* **2020**, 1–13. [CrossRef]
26. Aly, N.M. A review on utilization of textile composites in transportation towards sustainability. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2017.
27. Singha, A.S.; Rana, R.K. Natural fiber reinforced polystyrene composites: Effect of fiber loading, fiber dimensions and surface modification on mechanical properties. *Mater. Des.* **2012**, *41*, 289–297. [CrossRef]
28. Liu, W.; Drzal, L.T.; Mohanty, A.K.; Misra, M. Influence of processing methods and fiber length on physical properties of kenaf fiber reinforced soy based biocomposites. *Compos. Part B Eng.* **2007**, *38*, 352–359. [CrossRef]
29. Bledzki, A.K.; Faruk, O. Wood Fiber Reinforced Polypropylene Composites: Compression and Injection Molding Process. *Polym. Plast. Technol. Eng.* **2004**, *43*, 871–888. [CrossRef]
30. Singha, A.S.; Thakur, V.K. Mechanical properties of natural fibre reinforced polymer composites. *Bull. Mater. Sci.* **2008**, *31*, 791–799. [CrossRef]
31. Singha, A.S.; Thakur, V.K. Saccaharum Cilliare Fiber Reinforced Polymer Composites. *E J. Chem.* **2008**, *5*, 782–791. [CrossRef]
32. Zampaloni, M.; Pourboghrat, F.; Yankovich, S.; Rodgers, B.; Moore, J.; Drzal, L.; Mohanty, A.; Misra, M. Kenaf natural fiber reinforced polypropylene composites: A discussion on manufacturing problems and solutions. *Compos. Part A Appl. Sci. Manuf.* **2007**, *38*, 1569–1580. [CrossRef]
33. Takemura, K.; Minekage, Y. Effect of molding condition on tensile properties of hemp fiber reinforced composite. *Adv. Compos. Mater.* **2007**, *16*, 385–394. [CrossRef]
34. Lokesh, P.; Surya Kumari, T.S.A.; Gopi, R.; Loganathan, G.B. A study on mechanical properties of bamboo fiber reinforced polymer composite. *Mater. Today Proc.* **2020**, *22*, 897–903. [CrossRef]
35. Ameri, E.; Laperrière, L.; Lebrun, G. Mechanical characterization and optimization of a new unidirectional flax/paper/epoxy composite. *Compos. Part B Eng.* **2016**, *97*, 282–291. [CrossRef]
36. Sapuan, S.M. *Composite Materials: Concurrent Engineering Approach*; Butterworth-Heinemann: Boston, MA, USA, 2017; pp. 57–93.
37. Kalpakjian, S.; Schmid, S.R. Plastics and Composite Materials: Forming and Shaping. In *Manufacturing Engineering and Technology*, 6th ed.; Kalpakjian, S., Schmid, S.R., Eds.; Prentice Hall: Singapore, 2010; pp. 484–524.
38. Jaafar, J.; Siregar, J.P.; Tezara, C.; Hamdan, M.H.M.; Rihayat, T. A review of important considerations in the compression molding process of short natural fiber composites. *Int. J. Adv. Manuf. Technol.* **2019**, *105*, 3437–3450. [CrossRef]
39. Saravanan, K.; Dhurai, B. Effect of process parameters on impact strength of short jute fibre reinforced polypropylene composite board. *Indian J. Fibre Text Res.* **2013**, *38*, 92–95.
40. Tungjitpornkull, S.; Sombatsompop, N. Processing technique and fiber orientation angle affecting the mechanical properties of E-glass fiber reinforced wood/PVC composites. *J. Mater. Process. Technol.* **2009**, *209*, 3079–3088. [CrossRef]
41. Elamri, A.; Abid, K.; Harzallah, O.; Lallam, A. Characterization of Recycled/Virgin PET Polymers and their Composites. *Am. J. Nano Res. Appl.* **2015**, *3*, 11–16. [CrossRef]
42. Park, C.H.; Lee, W.I. Compression molding in polymer matrix composites. In *Manufacturing Techniques for Polymer Matrix Composites (PMCs)*; Elsevier: Amsterdam, The Netherlands, 2012; pp. 47–94. [CrossRef]
43. Syahirah, S.; Hazwani, N.; Faizin, A.; Farhan, M. *Design and Development of Heating Press System for Compression Molding Part 2*; Faculty of Mechanical Engineering, Universiti Malaysia Pahang: Pahang, Malaysia, 2016.

44. Barone, J.R.; Schmidt, W.F.; Liebner, C.F.E. Compounding and molding of polyethylene composites reinforced with keratin feather fiber. *Compos. Sci. Technol.* **2005**, *65*, 683–692. [CrossRef]
45. Kumar, A.; Srivastava, A. Preparation and Mechanical Properties of Jute Fiber Reinforced Epoxy Composites. *Ind. Eng. Manag.* **2017**, *6*. [CrossRef]
46. Vijay, R.; Singaravelu, D.L. Experimental investigation on the mechanical properties of Cyperus pangorei fibers and jute fiber-based natural fiber composites. *Int. J. Polym. Anal. Charact.* **2016**, *21*, 617–627. [CrossRef]