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Design and Fabrication of High-Load Bearing Bio-Composites Reinforced with Flax Fibers

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A B S T R A C T

This study, conducted to explores the development of renewable composites for high-load bearing automotive parts. Three flax reinforcements-non-woven thick mat, balanced fabric, and unidirectional fabric-were combined with bio-sourced epoxy resin to evaluate their mechanical properties. The research details the manufacturing processes for each material, emphasizing the unique handling requirements of plant-based fibers. Multiple laminates were fabricated and machined into specimens for tensile, compression, shear, and impact testing in accordance with ASTM standards. This comprehensive approach allowed for the identification of the most suitable material for industrial applications. The investigation provides valuable insights into the fabrication and performance of flax-reinforced composites, contributing to the growing body of knowledge on sustainable materials for automotive manufacturing. The promising results open new avenues for the implementation of renewable composites in structural applications, potentially revolutionizing the automotive industry's approach to sustainable, high-performance materials.

Keywords:Flax, PLA, biocomposites, mechanical properties, automotive

1. Introduction

The automotive industry is undergoing a significant transformation, driven by the need for more sustainable and environmentally friendly materials [1-3]. Bio-composites, particularly those reinforced with natural fibers, have emerged as promising alternatives to traditional petroleum-based composites [4]. These materials offer numerous advantages, including a neutral carbon footprint, biodegradability, and impressive specific mechanical properties [5-6]. However, despite their potential, the widespread adoption of bio-composites in high-load bearing automotive applications has been hindered by uncertainties surrounding their mechanical performance under various environmental conditions and loading scenarios [7-10].

This study focuses on the development and characterization of flax fiber-reinforced bio-composites for use in structural automotive components [11-12]. Flax fibers have gained considerable attention due to their excellent mechanical properties and renewable nature. By combining these fibers with bio-sourced epoxy resins, we aim to create high-performance materials that can meet the demanding requirements of the automotive industry while significantly reducing environmental impact [13-15].

The research addresses several key challenges in the field of bio-composites. Firstly, it explores the manufacturing processes for different flax reinforcements, including non-woven thick mats, balanced fabrics, and unidirectional fabrics [16-18]. Each of these reinforcement types presents unique handling and processing challenges inherent to plant-based fibers. By detailing these processes, we contribute valuable insights into the practical aspects of bio-composite production, which is crucial for future industrial scale-up. Secondly, this study conducts a comprehensive mechanical characterization of the developed bio-composites [19-21]. Through rigorous testing in accordance with ASTM standards, we evaluate the materials' performance under tensile, compression, shear, and impact loads. This thorough assessment is essential for understanding the full range of mechanical behaviors exhibited by flax-reinforced composites and for identifying the most suitable material combinations for specific automotive applications [22-25]. Moreover, our research aims to bridge the gap between laboratory-scale development and industrial implementation. By considering manufacturing protocols that are scalable and compatible with existing automotive production techniques, we ensure that our findings have practical relevance for the industry [26-29].

The potential impact of this research extends beyond the immediate scope of material development. By demonstrating the viability of flax-reinforced bio-composites for high-load bearing applications, we contribute to the broader goal of reducing the automotive industry's environmental footprint [30-32]. The use of these materials could lead to lighter vehicles, resulting in lower fuel consumption and reduced emissions. Additionally, the biodegradability of these composites addresses end-of-life concerns, aligning with circular economy principles [33]. As we progress through this study, we aim to not only identify the most promising flax-reinforced bio-composites but also to lay the groundwork for future innovations in this field [34-

35]. By systematically investigating the relationship between material composition, manufacturing processes, and mechanical properties, we hope to provide a comprehensive understanding that will guide future research and development efforts in sustainable automotive materials [36-40].

2. Materials

Flax fiber is showin in figure 1. Composites Evolution developed a fabric that features a blend of 2x2 twill, combining flax and Poly(L-lactide) acid (PLA) fibers. The PLA fibers, which come from corn starch through fermentation, were provided by Natureworks. To compare, samples made from flax and epoxy were also analyzed [41-42]. All the samples were made by MaHyTec. A well-balanced fabric, FlaxPly BL300, made from a woven flax fabric and a bio-based epoxy resin, Epobiox LV, mainly from epoxidized pine oil waste and its Ca23 hardener, both made by Amroy, were successfully created.

Fig. 1 - Flax fiber.

2.1 Natural fibers

The decision on which natural fibers to employ for strengthening the vehicle's structural components is crucial because their characteristics will largely dictate the material's mechanical strength [43-45]. The criteria for choosing these fibers include a high longitudinal Young’s modulus, a low density, the capability for industrial-level production, and the market availability of technical-grade semi-finished materials [46-50]. Adhering to these criteria, flax and hemp fibers emerged as the top contenders. Table 1 outlines the mechanical attributes of these fibers when compared to glass fibers.

Table 1 - Properties if HEM and Glass fiber

Fiber	% of Elongation	Youngs Modulus	Strength	Density
Hemp	1-5	35	390	1.5
Flax	1-5	70	500-2000	1.45
Glass	4-8	70-75	3000-3500	2.5

The research on the market for natural fibers highlighted the challenge in locating specialized hemp products due to the varied uses of hemp: for example, as insulation and for decorative purposes [51-53]. However, a number of flax-derived partially processed goods were found instead. Three specific items were chosen and bought for testing purposes: a flax evenly woven fabric, a flax thick non-woven mat, and a flax one-directional fabric (see figure 2). The characteristics of these items are detailed in table 2 [54-57].

Table 2: Properties of Flax

Type of Materials	Weight of Materials	Thickness of Materials	Density
Non-Woven	1200	5	--
UD	180	0.3	1.2
Constant Fabric	300	0.5	1.2

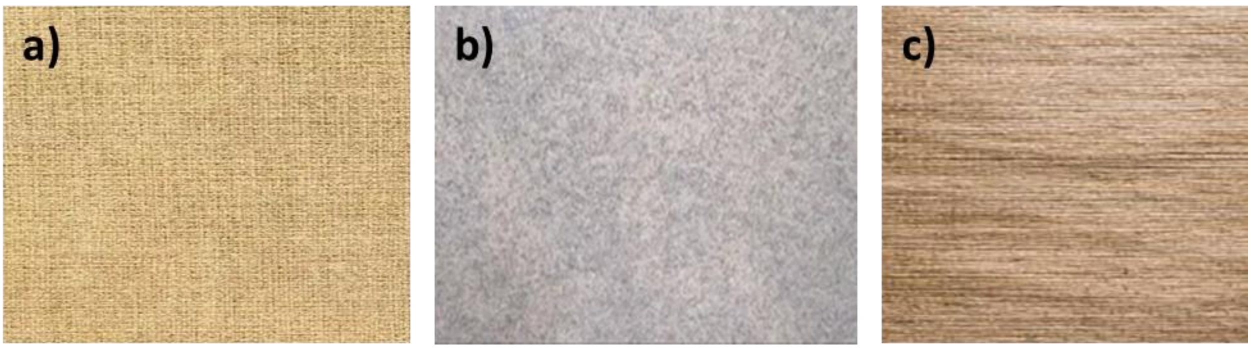

Fig. 2 - a) Non-Woven b) UD c) Same Fabric

2.2 Resins

The waste left after using products accounts for 24.3 million tons, with 54% being recycled or directly used to produce energy, amounting to 5.5 million tons recycled and 7.6 million tons used this way. The rest, 46%, or 11.2 million tons, ends up in landfills. The environmental effects of the plastic sector are a serious issue, and finding a way to replace plastics made from fossil fuels with those made from renewable plant-based materials is seen as a promising solution.

To explore and evaluate three types of materials: a typical epoxy resin, a resin made from biological sources, and a resin made entirely from renewable tannins. This study is specifically about how these resins behave under stress [58-60]. To deal with a temporary lack of available bio-epoxy resin, a natural fiber called flax was soaked in a usual epoxy solution, believing that it wouldn't noticeably impact the strength of the final composite samples [61]. It's important to mention that other factors, including how much water the material absorbs, were also looked into to thoroughly compare these plant-based products to traditional, non-biodegradable plastics.

3. Advanced Techniques in Composite Laminate Production

3.1 Fabrication Technique

Mahytec conducted the production of all bio-composite laminates through the hot compression molding method. These composite plates were molded with a 100t hydraulic press equipped with servo-actuators for precise pressure control during the consolidation process. The pressing blocks were integrated with an electric furnace equipped with a multi-segment controller for the scheduling of polymerization processes. To monitor the temperature as accurately as possible, a thermocouple with a narrow diameter was installed in the mold [62-64]. The initial tests underscored the need to decrease the thermal lag of the mold to pinpoint the ideal curing and consolidation stages. Therefore, a slim-walled aluminum mold was employed for this purpose. To ensure adherence to high standards and reproducibility, a rigorous mold preparation process, from polishing and removing polymeric residues with a cleaning solvent and release agent, was implemented before composite curing [65]. Every flax product was linked to a designated consolidation cycle, and the production of uniform and fully saturated composite materials necessitated considering their unique characteristics.

3.2 Flax fibers preparation

Every material required a specific and universal process: the drying of the flax fibers. Similar to other natural fibers, flax fibers are highly susceptible to soaking up water when kept under standard conditions. A high moisture level in the fibers results in weak bonding between the fibers and the matrix, which means a subpar transfer of stress to the fibers when subjected to mechanical forces, along with significantly reduced mechanical strength [66-67]. This weak bond between the resin and the fibers, due to inadequate drying, was noted in the initial production tests (figure 3), even after using a release agent on the pressing block surfaces: despite the use of a release agent on the mold surfaces, pieces of resin were pulled out of the composite plate and stuck to the mold because there was no bonding with the flax fibers. Eventually, an appropriate drying method was discovered, enabling the creation of well-soaked flax-reinforced plates.

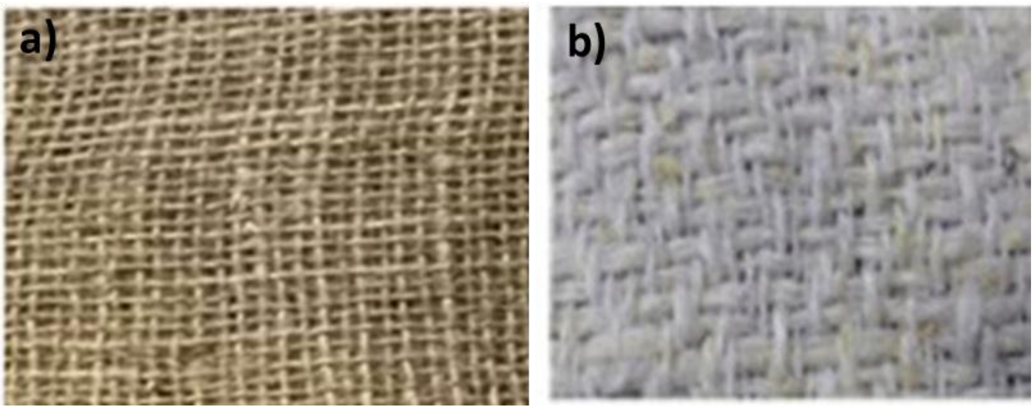

Fig. 3 - a) Flax epoxy with resin before dry, b) Flax epoxy with free porous after dry

3.3 Advanced Methods for Impregnating and Consolidating Flax Layers

The number of layers varied based on the type of flax product, with a target thickness of approximately 3mm being achieved through a mix of layers. For the balanced fabric, five layers were utilized, while the unidirectional fabric required seven layers, and the non-woven mat only needed one layer

[68-70]. Each layer was trimmed to fit the mold's size (270*270mm). Trimming the unidirectional layers required extra caution to prevent the separation of the weft fibers and to avoid distorting the fabric, which could cause the warp fibers to become misaligned. After the flax fibers were thoroughly dried, the layers were hand-coated with epoxy resins. The larger thickness of the flax mat made it more challenging to achieve complete coating. This issue was addressed by modifying the hand-coating method and increasing the compression force. After the curing process, cross-sectional examinations of the mat-reinforced plates revealed a uniform distribution of the epoxy resin throughout the plate's thickness.

For each combination of materials, a specific time was allocated for the resin to thicken before applying the compression force. The force was applied incrementally, and the curing process began at the same time. The compression settings were adjusted to achieve a weight fiber content of 50%. Depending on the specific resins and hardeners used, one or two temperature stages were set. Figure 4 illustrates plates that were successfully impregnated after being removed from the mold.

Fig. 4 - Flax fiber unidirectional and non-woven fiber after dry Mold

4. Testing specimens machining

The plates were employed in the process of working on different samples as part of a comprehensive mechanical characterization initiative, which involved tests for tension, compression, shear, and impact. The table 3 contains summaries for each test, detailing the ASTM standards applied, anticipated results, sample shapes, and velocities of loading:

Table 3: Operating conditions for the experimental characterization campaign

Static Test			
	Tensile	**Compression**	**Shear**
Standard	ASTM D3039	ASTM D3041	ASTM D7078
Outcomes	Strain, Poission ratio, Stress-strain curve, Tensile strength	Strain, Poission ratio, Stress-strain curve, compression strength	Stress-strain curve, shear strength
Specimen	250x20mm	150x20mm	Section V
Loading	3mm/min	1.5mm/min	2.5mm/min

Experimentations included impact evaluations with weights dropped to varying heights, covering levels of 1.4, 4.5, and 10 Joules. For each material, eight pieces were created through machining, with the exception of the impact tests, where only four pieces were utilized. To perform tensile and compressive strength tests, four aluminum strips, each measuring 50 millimeters in length, were attached to the samples using a two-way adhesive known as a bi-components epoxy. The panels intended for composite analysis were shaped using a numerical milling device. The process is depicted in Figure 5.:

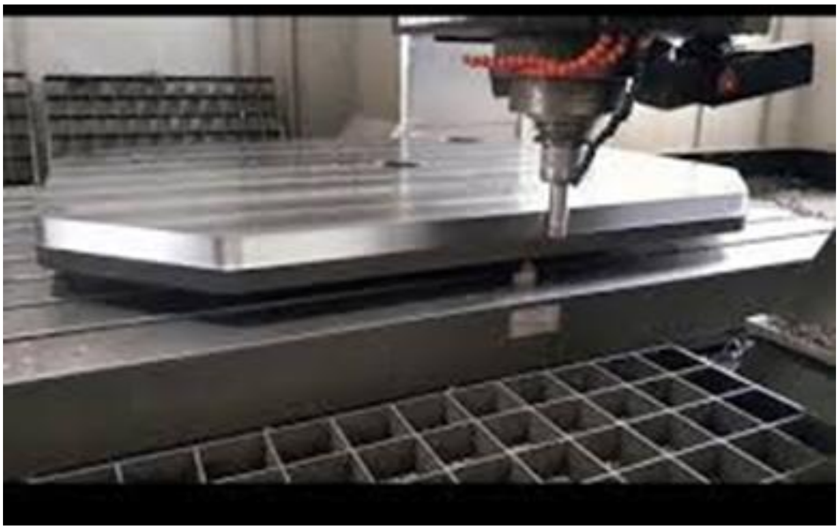

Fig. 5 - Test setup for milling

Fig. 6 - Presents the set of testing specimens extracted from non-woven flax/bio-epoxy composite plates:

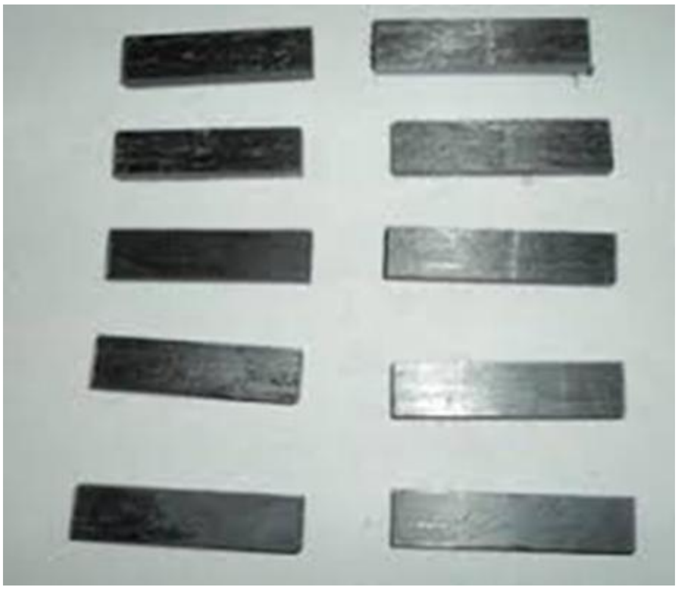

Fig. 7 - Set of flax mat/bio-epoxy testing specimens

5. Experimental results

Every mechanical examination was conducted by Cranfield University. In total, 82 samples needed to undergo testing. As of the time of this writing, the experimental project was not yet completed, and only a fraction of the results are available here. Nonetheless, these initial findings provide a clear understanding of the flax materials' mechanical properties.

5.1 Tensile testing

Table 4 summarizes the tensile tests results obtained on the three flax/epoxy materials.

Table 4: Tensile tests results obtained on the three flax/epoxy materials.

Type of Materials	Youngs Modulus	Ultimate strength	% strain
Non-Woven	77.1	8.15	1.2
UD	223.2	22.89	1.35
Constant Fabric	89.11	8.10	1.92

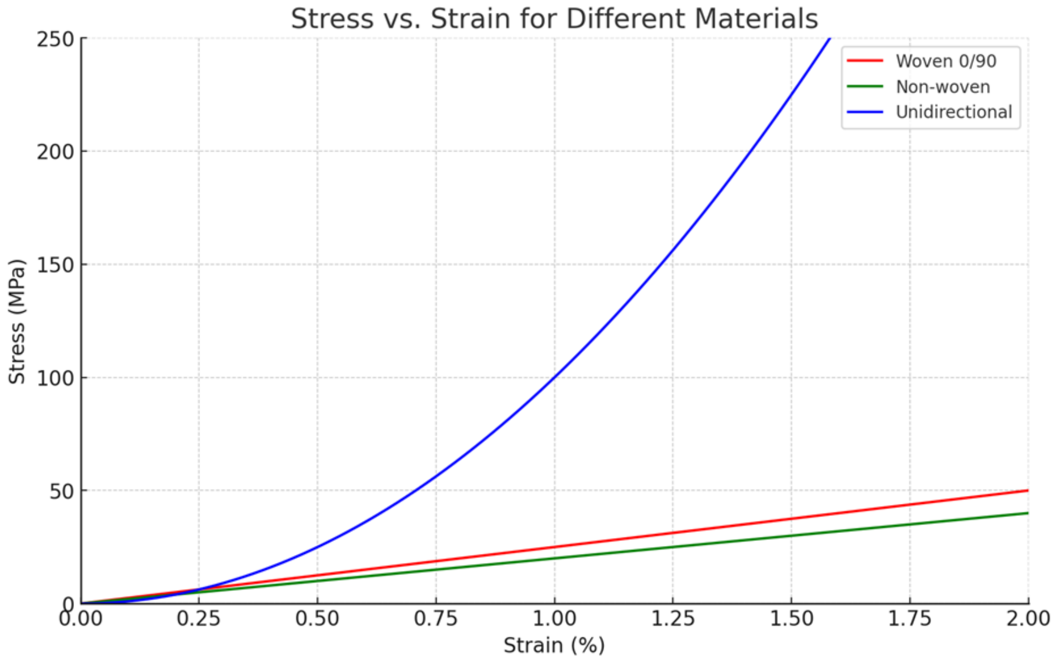

Fig. 8 - Stress vs strain for different materials

As anticipated, the addition of UD reinforcement resulted in significantly increased tensile strength and rigidity, with values that closely matched the mechanical standards outlined by the vehicle's design. What was even more unexpected was that the equilibrium fabric performed as well, if not better, than the thick mat. This could be attributed to the rough weave structure and the undulation of both warp and weft fibers.

5.2 Compression results

The results from compression tests conducted for the woven and non-woven materials are presented in table 5:

Table 5: Compression test results

Type of Materials	Compression Strength	Compression Modulus	Failure
Non-Woven	110.1	8.01	2-4
Constant Fabric	107	8.21	1.8-2.5

As anticipated, the material under compression exhibits a higher strength than its counterpart when it comes to tensile strength, while the stiffness level tends to be roughly constant. Surprisingly, the fabric made from non-woven material surpasses the strength of the balanced fabric, primarily because of the irregularity in the fiber arrangement. It's not possible to precisely determine the strain at failure, as the samples don't burst apart but instead fail in a gradual manner due to the fibers breaking near the center of the test length.

5.3 Shear results

Figure 8 illustrates the failure behaviors of the three materials under shear stress reveal distinct failure mechanisms. The fracture in the symmetrical material is nearly parallel to the notch, bridging the two opposite edges. This failure is abrupt and rigid, devoid of any noticeable plastic bending, and is regulated by the material's matrix strength. Although the fibers don't rupture past 40% of the composite's initial shear strength exists, making the sample technically failed. The shear strength and stiffness for the symmetrical material were found to be 52.1 MPa and 2.2 GPa respectively. The failure lines for the non-woven material are chaotic, tracing the path of the least resistance between the fibers and the material. However, the start of the failure is concentrated at the notch edge's middle, where the stress is at its peak. No cracks are noticeable before failure, and the subsequent failure occurs suddenly and without resilience, reaching a strength of 49.5 MPa and a stiffness of 2.1 GPa. According to the ASTM standard D7078, testing of unidirectional specimens is discouraged due to imprecise measurement estimations. In this study, the results for unidirectional specimens are also reported for comparative analysis. A crack appears at the junction of the notch's root once the strain reaches 1.5% and the shear stress is 32 MPa, resulting in a reduction of load by 5%. The crack then extends parallel to the fiber direction until failure. Despite an increase in force and stress following the crack's formation, the testing was ceased as the samples were deemed to have failed.

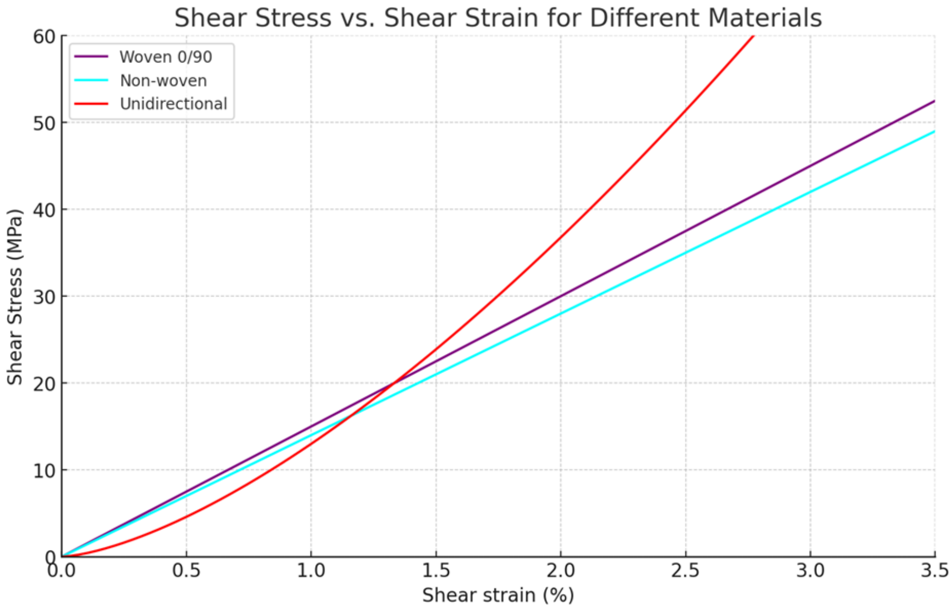

Fig. 9 - Shear stress vs shear strain for different materials

Fig. 10 - Specimen sample

6. Conclusions and perspectives

This ongoing research has significantly advanced our understanding of flax-reinforced materials, both in terms of manufacturing protocols and mechanical behavior. The experimental results, demonstrating remarkable strength and stiffness under various loading conditions, confirm the viability of these materials for structural applications in the automotive industry. The comprehensive testing regime, encompassing tensile, compression, shear, and impact evaluations, provides a robust foundation for assessing the performance of these bio-composites in real-world scenarios. Moving forward, our research will focus on the hybridization of flax reinforcements within single laminates. This innovative approach aims to capitalize on the unique properties of each material type, potentially leading to optimized combinations tailored for specific vehicle components. By strategically combining different flax reinforcements, we anticipate achieving enhanced mechanical properties and performance characteristics that surpass those of individual materials.

The promising results obtained thus far open up new possibilities for the automotive industry to adopt sustainable, high-performance materials without compromising on structural integrity or safety. As we continue to refine our understanding and techniques, the potential for widespread implementation of these bio-composites in automotive manufacturing grows increasingly tangible, marking a significant step towards more environmentally friendly and resource-efficient vehicle production.

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