

Evaluating the Performance of Composite Tubes Drawn from Hybrids of Aluminum, Steel, and Carbon Fiber

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Abstract. Present demands for weight reduction of vehicles to decrease the carbon footprint in the transport industry have increased the need for lightweight tubes. In this paper, composite tubes are drawn from two aluminum tubes and reinforcements with the aim of maximizing mechanical performance while maintaining low weight. The reinforcements are placed between the two aluminum tubes and are made from blanks of 22MnB5 steel or carbon fiber laid in different quantities and patterns. The compressive stresses in tube sinking are used to hold the reinforcements in the composites without the need for resins and energy-intensive heating or curing cycles. The composites are weighed, and their performance is evaluated by mechanical test. Bending tests reveal an increase in the bending strength of the reinforced tubes by 15% for both composites reinforced by carbon fiber and 22MnB5 steel. However, the composites made from carbon fiber have higher stiffness and lower weight. The bending strength and residual stresses of composites manufactured with different carbon fiber layouts and quantities are evaluated to determine their performance. Increasing the carbon fiber content did not improve the stiffness and ultimate tensile strength of the composites, indicating the compressive stresses from drawing and carbon fiber content should be optimized to achieve the best mechanical performance.

Introduction

In many industries composite tubes are required to exploit the beneficial properties of the constituents. Such is the case when high temperature resistance, high strength, and corrosion and wear resistance are required for pipes in the petrochemical industry, marine applications, power and gas, and water and heat supply. The most basic type of composite tubes are bimetallic tubes, made up of a base tube (outer) that satisfies the mechanical requirements and a cladding tube (inner) that meets other special requirements. The deformation of the base tube is usually higher than the cladding tube [1]. The process outcome in the drawing of bimetallic tubes is determined by parameters like the thicknesses of the different tubes, die angle, friction coefficients between the surfaces, and value of deformation [2]. Composites requiring more than two tubes are mainly used in thermal insulation applications [3].

Composite tubes containing carbon fibers are used in lightweight applications in the aerospace and automobile industries due to their high stiffness and high strength-to-weight ratios [4]. Carbon fibers possess high specific energy absorption and have been used as reinforcement to improve the crash resistance of tubes [4]. Fibers can be laid in different ways to create composite tubes with varying mechanical properties along the tube circumference, which allows for even further weight reduction. The optimum quantity and layout of fibers required to maximize mechanical performance of components has been the subject of a lot of research. Composite tubes are mostly made from fibers woven on metal tubes [5]. The manufacturing process chain of carbon fiber reinforced components usually includes heating and curing cycles, which are expensive and energy intensive [6].

This study investigates the tube drawing of composite tubes that consist of EN AW-6060 aluminum tubes reinforced with 22MnB5 steel blanks and carbon fiber. 22MnB5 steel was chosen as reinforcement material because its high buckling and compressive strengths are required to relieve pressure, while carbon fiber is selected because of its good tensile properties and lightweight. The

22MnB5 blanks and carbon fiber are arranged between two concentric tubes in the desired layouts before the drawing step, as indicated in Fig. 1. Unlike conventional hybrid composite manufacturing methods that require adhesive bonding, resins, heating, and curing cycles, the present approach uses tube drawing–induced compressive stresses to mechanically consolidate reinforcements, thus achieving a manufacturing process with a lower cost and environmental impact.

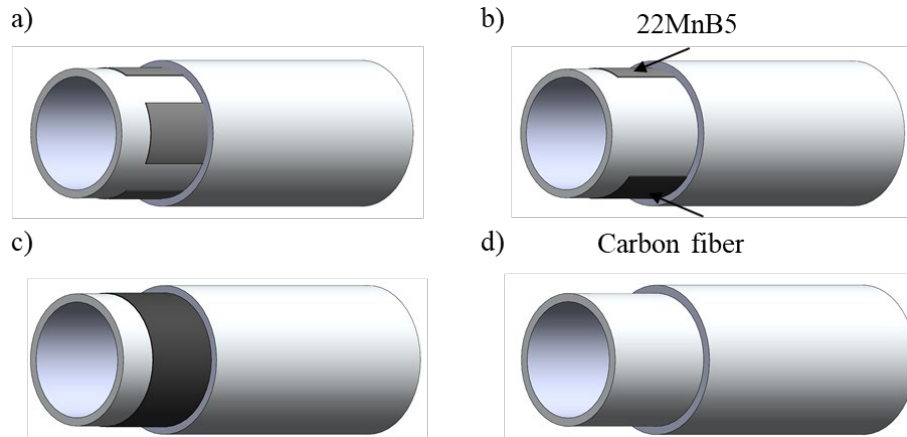


Fig. 1. Representations of the reinforcements used in the composites. a) Four 22MnB5 blanks. b) One carbon fiber band and one 22MnB5 blank. c) Carbon fibers laid along the length and circumference of the tube. d) Control experiment.

Materials and Methods

Two EN AW 6060 AlMgSi0.5 aluminum tubes with 18 mm and 20 mm external diameters were used as the matrix. The tubes were cut to 1 m length and had 1 mm wall thickness. The 18 mm tube, which serves as the inner tube, was drawn to 16 mm in one forming step. Reinforcements made from either carbon fiber or 22MnB5 blanks rolled to 0.2 mm thickness and 9 mm width were placed on the inner tubes. The carbon fiber designation was Tenax UTS 5131 800tex F12000 T 0 with a diameter of 7 μm and ultimate tensile strength above 4500 MPa. About 10 fibers were along the thickness of the carbon fiber bands.

The tubes were reinforced using the following reinforcement methods: 1. A carbon fiber band and one 22MnB5 blank. 2. Four 22MnB5 blanks laid along the tube length. 3. Carbon fiber laid along the length of the tube and a second layer across the length of the tube. A control experiment with no reinforcement was performed. The inner tubes with the reinforcement were placed into the larger tubes (20 mm), as shown in Fig. 2. The resulting composites made from aluminum, carbon fiber, and/or steel were drawn to reduce the tube diameter from 20 mm to 18 mm in two steps, see Fig. 2c. The drawing velocity was 2 m/min. The experiments were conducted on a 500 kN drawing machine manufactured by Bültmann Maschinenbau GmbH & Co. KG.

Tensile, compression, and bending tests were performed on the formed composites on a Zwick-Roell universal testing machine. Three repetitions of the tests were performed. Samples were cut from the composites and weighed.



Fig. 2. a) Carbon fiber reinforcement placed along the length and circumference of the inner tube. b) Stacking the two tubes with carbon fiber reinforcement to form a composite. c) The composite drawing process.

Given the dependence of the performance of composites reinforced with carbon fiber on layout and alteration in the shape of composites, the mechanical properties and residual stress of composites made from different fiber layouts were investigated. The residual stresses were measured from 0.05 mm below the surface of the tubes to 0.5 mm at increments of 0.05 mm using the hole-drilling method on a Stresstech prism hole drilling system, Stresstech Oy, Vaajakoski, Finland.

Results

Weights. The weights of the composites were evaluated by weighing 20 mm lengths of the composites, see Table 1. As expected, the non-reinforced tubes had the minimum weight (0.2909 g/mm). The composite with carbon fiber had a higher weight of 0.3035 g/mm. The composite with carbon fiber and one band of 22MnB5 reinforcement weighed 0.30365 g/mm. The maximum weight was for the composite with four 22MnB5 blank reinforcements (0.33435 g/mm). More detailed investigations were performed on the carbon fiber reinforced tubes given their potential in light weighting.

Table 1. Composite weights

Composite type	No reinforcement	Carbon fiber ring	1 carbon fiber band + 1 22MnB5 blank	four 22MnB5 blanks
Normalized weight (g/mm)	0.29090	0.30350	0.30365	0.33435

Micrographs. Cross sections of the tubes are shown in Fig. 3. The black arrows indicate reinforcements. In between the 2 tubes, four 22MnB5 blanks are seen in Fig. 3a, the carbon fiber band and 22MnB5 blank are shown in Fig. 3b, and the carbon fiber in Fig. 3c. The size of the carbon fiber band can be further reduced by using more drawing sequences or by employing a mandrel to provide compressive forces on the inner wall. The tubes with no reinforcement are shown in Fig. 3d. The composite with a carbon fiber band and 22MnB5 blank in Fig. 3b appears to be less circular due to the presence of reinforcements at only two ends of the tube circumference.

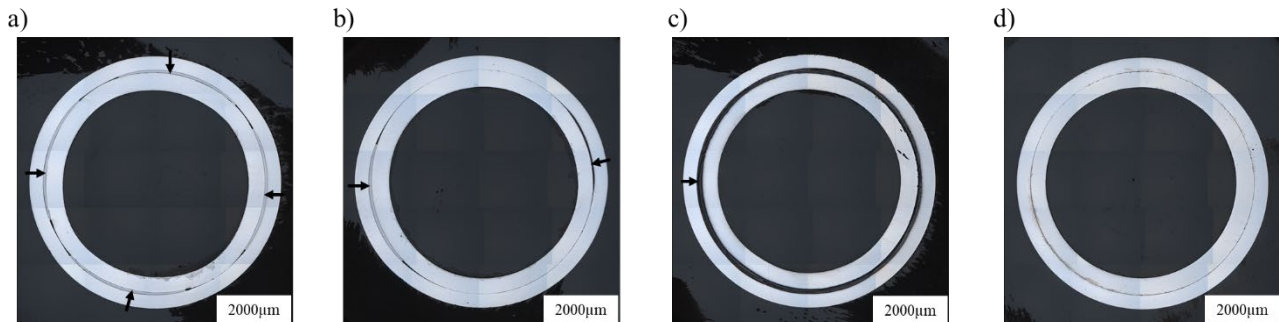


Fig. 3. a) Composite with four 22MnB5 blanks. b) Composite with a carbon fiber band and one 22MnB5 blank. c) Composite with carbon fiber laid along and across the tube length. d) Tubes with no reinforcement.

Compression tests. The forces in compression tests of the non-reinforced tubes and carbon fiber composites are presented in Fig. 4. The results reveal that the presence of the carbon fiber leads to a slight decrease in the maximum force sustained by the tubes before failure. The compressed tubes in Fig. 4 reveal larger deformed bases of the carbon-reinforced tubes than the tubes with no reinforcement.

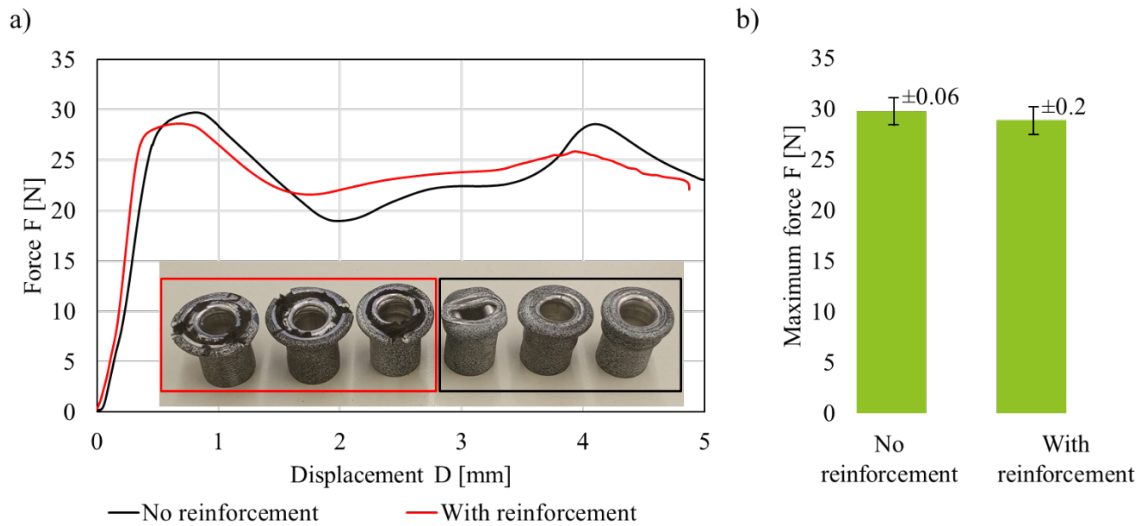


Fig. 4. a) Force evolution in compression tests of the composites with carbon fiber reinforcement and without reinforcement. b) Maximum force in compression tests.

Tension tests. Tension tests on the non-reinforced tubes and carbon fiber reinforced composites are presented in Fig. 5. The composite had a higher stiffness than the non-reinforced tubes. The non-reinforced tube was stretched to 4% elongation, while failure of the carbon fiber reinforced specimen was abrupt just after the yield strength.

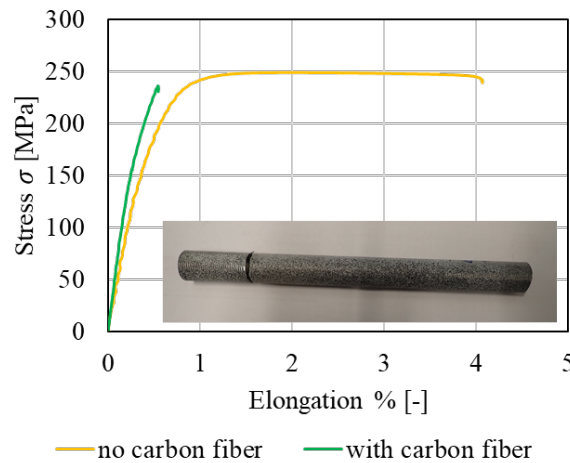


Fig. 5. Force evolution in tension tests of the composites with carbon fiber reinforcement and without reinforcement.

Bending tests. The results of bending tests performed on the specimens are presented in Fig. 6. The least maximum bending forces were measured for the non-reinforced specimen. The composite with carbon fiber and one 22MnB5 blank supported a higher maximum force of about 4300 N. The composites with carbon fiber and four 22MnB5 blanks had higher maximum forces of about 4500 N. The highest stiffness was measured for the carbon-reinforced tube, followed by the composite with carbon fiber and one 22MnB5 blank, and the composite with four 22MnB5 blanks. There was an abrupt fall in the bending forces for the composite with four 22MnB5 blanks after attaining the maximum load at a displacement of about 12 mm. The drop-in force is due to the failure of some 22MnB5 blanks. Carbon fiber has a higher tensile strength than steel and is placed on the bottom (outside of the bend), while the 22MnB5 blank was placed on the inside of the bend when testing the composite reinforced with 22MnB5 steel and carbon fiber. After attaining the maximum bending load, the forces decrease due to wrinkle formation and fracturing of the tube. The forces at the end of the bending tests increase for the carbon fiber reinforced composites, probably due to the carbon fiber carrying the load after the matrices begin to fracture. The increase in forces at the end of the bending experiments of the composite with carbon fiber may be beneficial in crash applications, since the toughness (area under the curve) is higher.

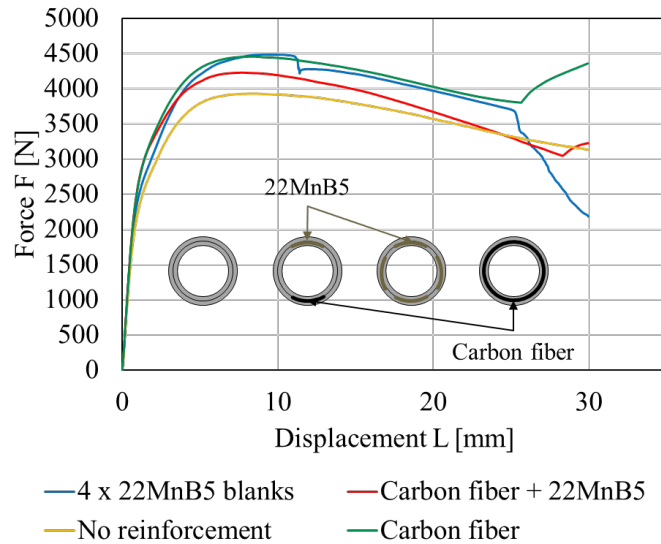


Fig. 6. Force evolution in bending tests.

Fig. 7a presents the bent composite tubes. The widths at the bends are presented in Fig. 7b. The sudden drop in the force displacement curve of the tube reinforced with 22MnB5 in Fig. 6 is due to the presence of cracks, as shown in Fig. 7a, which interrupted the evolution of the width at the bend. The other specimens have no cracks. The width of the bent tube with no reinforcement was the least. The widths of the bends of the composites with carbon fiber were higher than the tube with no reinforcement and can be explained by the presence of carbon fiber. The composite with a carbon fiber and 22MnB5 blank had the highest width of the bend, which can be explained by the stiffness of the 22MnB5 blank resisting bending and causing widening of the tube.

a)



b)

Type	Bulge width (mm)
4x22MnB5	25.46
Carbon fiber +22MnB5	26.13
No reinforcement	24.48
Carbon fiber	25.96
3 bands spread	25.83
3 bands stacked	25.70

Fig. 7. Force evolution in bending tests.

To study the fibers at fracture, the bending test of the fiber-reinforced composite was continued to fracture. Scans of the fractured composites are presented in Fig. 8. The global scan of the fractured surface shows the ends of the fractured aluminum tube and carbon fibers in Fig. 8a. Closer scans in Fig. 8c and Fig. 8d reveal that a few fibers were broken in the bending test, while most of the ≈ 10 fibers along the band thickness are unbroken. The first fiber layer on the inner surface sticks to the surface of the inner aluminum tube. This means that most fibers do not stretch or tear, even though the aluminum on the tension side was stretched significantly.

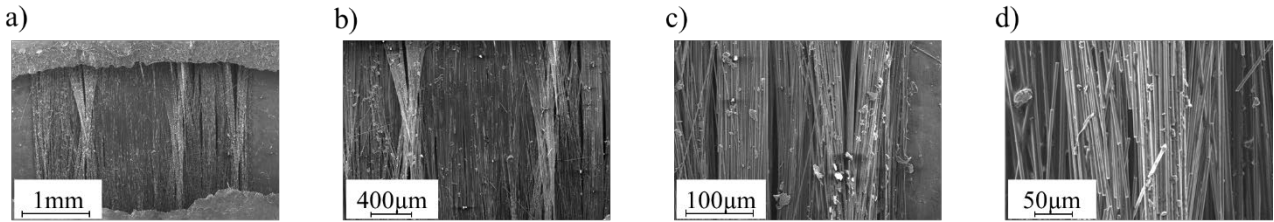


Fig. 8. Scans of fractured surface of the carbon fiber reinforced composite at different magnifications.

Variable carbon fiber content. The carbon fiber content and layout were varied to study the bending stiffness, given that most of the fibers remain unbroken in the fiber-reinforced composite, and a smaller number of individual carbon fibers may be sufficient to achieve the same stiffness and load-carrying capacity. The carbon fibers were laid only along the outside of the bend since a higher bending stiffness is often required in specific directions in some applications. The composites were formed using a single carbon fiber band, three carbon fiber bands spread out, and three carbon fibers stacked on each other, see the cross sections represented in the legends in Fig. 9a and Fig. 9d.

The weight of the composite made with a single band was lower than those with 3 bands, as expected. The results of the bending tests in Fig. 9 reveal that the composite with a single band had a higher bending strength ($4285 \text{ N} \pm 70$) than the composites made from 3 bands ($4219 \text{ N} \pm 70$ for spread and $4142 \text{ N} \pm 50$ for stacked layouts). Residual stresses on the outer tube of composites with the single and three stacked carbon fiber bands are presented in Fig. 9d. The maximum residual stress was in the drawing direction for the 2 tubes on both sides of the composite with and without carbon fiber bands. The presence of carbon fiber increased the maximum residual stress, see the residual stresses in Fig. 9c and Fig. 9d. In the circumferential direction, there is no clear trend to explain the influence of carbon fiber on minor residual stress. The composite with the single band of carbon fiber had higher residual stress on the contact side than on the non-contact side of the tube, and vice versa for the composite with three stacked carbon fiber bands.

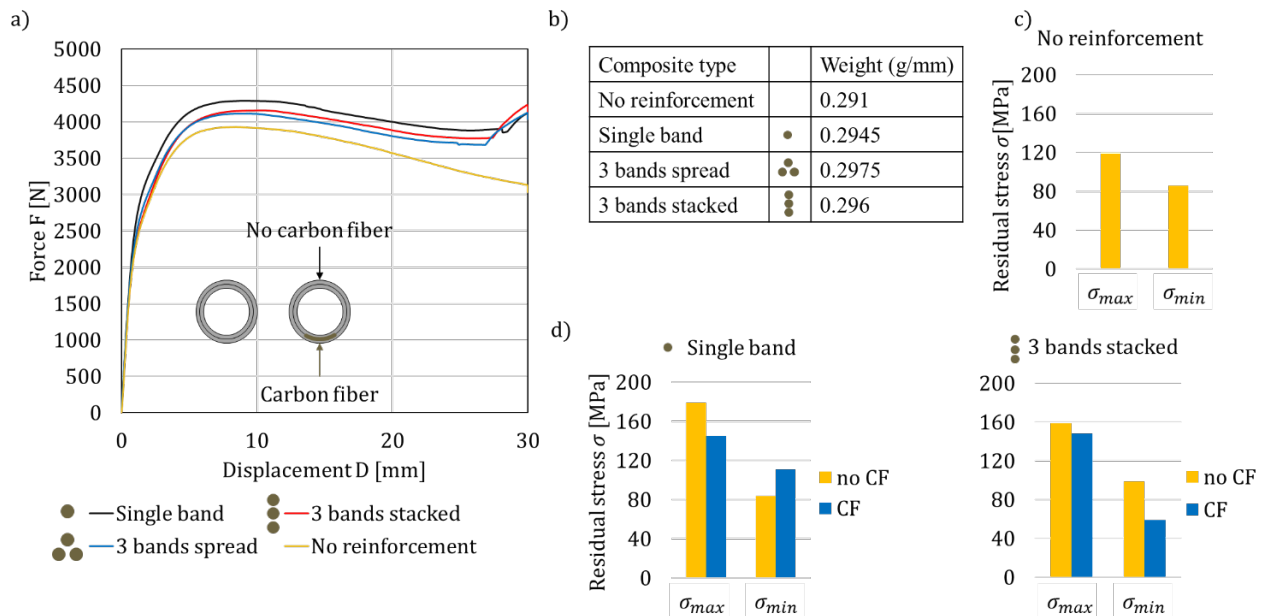


Fig. 9. a) Forces in the bending of composites. b) Weight of composites. c) Residual stresses of the non-reinforced tube. d) Residual stresses on the side with carbon fiber and no carbon fiber.

Discussion

Tube sinking of the composite is implemented to use the in-plane compressive stress in the process to restrain the reinforcements. Compression tests reveal no benefits accrued with the use of carbon fiber reinforced composites, instead, slightly early fracture was observed in the composites. The carbon fiber reinforced tubes had larger deformed bases than the nonreinforced tubes, which may be explained by the carbon fibers sliding past each other and reducing the friction between the two tubes and facilitating deformation. Similarly, tension tests demonstrate no benefit for the carbon fiber reinforced composite. The sudden drop in forces may be due to fracture caused by variable deformation and residual stresses induced by the presence of the carbon fiber band. In addition, the clamping condition may have influenced failure since the fracture occurred on the outer tube directly next to the clamping, as shown in Fig. 5. The bending experiments revealed that the carbon fiber reinforced composites have higher bending strength than the steel reinforced composites and the non-reinforced tube. This is due to the high ultimate tensile strength of carbon fiber (~ 4500 MPa) compared to 22MnB5 (~ 1650 MPa). However, the carbon fibers slipped past each other when 3 carbon fiber bands were used as shown in Fig. 8a, resulting in lower bending forces. Since carbon fibers are quasi-inextensible, the outer fibers slide towards the interior of the bend without stretching, resulting in lower bending forces [7]. Due to the high stiffness of carbon fiber relative to aluminum, the carbon fibers stick to the outer surface of the inner aluminum tube in bending. The detailed interactions between the fibers and aluminum tubes and between the fibers are impossible to control for the thousands of individual fibers [8]. However, properties of the components can be enhanced by reducing slippage of the carbon fibers through increasing the in-plane compressive stresses that hold the composite together. The in-plane compressive stresses can be increased by optimizing the drawing setups, the number of drawing steps, or using tube drawing with mandrels. An optimum quantity and layout of carbon fiber is needed to maximize the bending strength.

Conclusions

- Reinforcing the tubes with carbon fiber led to an increase in the maximum bending strength by 15% and a 1.2% increase in weight.
- The composites made from carbon fibers and 22MnB5 had the same bending strength. However, the lower weight of the carbon fiber reinforced composite makes it more suitable for lightweight applications.
- The carbon fiber reinforced composite had the highest stiffness, followed by the composite reinforced with carbon fiber and 22MnB5 steel. The composite reinforced by 22MnB5 steel had the least stiffness.
- Compression and tensile tests on the composite reveal limited benefits of using composites over base material.

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