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Using embossing to create tough polymeric-based structures

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Honeycomb-type structures can have a high stiffness-to-weight ratio. One way to create a honeycomb-type structure would be to use micromachining techniques to create a series of deep grooves in a polymeric material. We have created a honeycomb-type material by using a technique microembossing [1, 2]. Microembossing is a technology made possible by micromanufacturing processes which include micromilling and electron beam lithography. Such processes are capable of machining into metals and polymers [3] geometries with feature sizes ranging from the submicron level to hundreds of microns.

By machining microchannels or other geometric characteristics into metallic dies, detailed surface impressions can be obtained by pressing the dies into thin polymeric sheets under suitable conditions of pressure, temperature, and time [4, 5].

In this particular project, small grooves were machined into an aluminum plate. These grooves are on the order of 0.1 mm wide and 0.2 mm deep, with a wall thickness between grooves of about 0.06 mm. Using heat and pressure, the aluminum plate is then pressed into the polymeric sheet, producing grooves in the polymer. These thin sheets were then put together with the orientation of the grooves being different on each sheet. This creates a structure that has a high stiffness-to-weight ratio. It would be similar to creating a 0/90 layup of a conventional composite material where the "fibers" portion now being the walls between the grooves. The objective of this work was to create polymeric materials with an increased stiffness and toughness per unit weight by bonding a series of grooved polymeric sheets together to form composite plates.

We have used dies with both rectangular- and trapezoidal-shaped microchannels. An example of the trapezoidal-shaped channel is shown in Fig. 1. When this aluminum die was pressed into a 1-mm-thick polycarbonate sheet, the polycarbonate flowed filling up the grooves on the aluminum plate, thus creating a grooved polymeric sheet. A number of these sheets were then bonded together to form a composite. Rectangular-channeled material had to have a thin, unembossed sheet placed at the center to help complete the channels. With trapezoidal dies, this was not needed as two like layers are placed together to create a hexagonal-shaped channel. Fig. 2 shows two adjacent plies with the same channel orientation. Other combinations of orientation were also fabricated. Fibers were embedded into the channels in some of the laminates.

The embossing process was carried out at an elevated temperature in an environmental chamber attached to an MTS servo hydraulic testing machine [1]. After cooling, these sheets were removed from the embossing die. Removal of the embossed sheets from the die prior to cooling caused the sheets to warp. The large 25.4 cm × 25.4 cm embossed sheets were then cut into smaller pieces and bonded together using a thixotropic adhesive. One of the problems faced was obtaining the needed alignment of two trapezoidal channels in adjacent layers so that the hexagonal channel could be formed. The alignment was achieved by placing several hexagonal-shaped metal rods that just fit into the channels. Their presence forced the next layer's channels to be aligned with the previous layer's channels.

Bend tests, tensile tests, and Charpy impact tests were performed on laminates made from this material. To take into consideration the difference in density between the embossed and unembossed laminates, specific material properties were calculated by dividing the results of the tests by the specific gravity.

The mechanical test results were not, in all cases, an improvement over the unembossed results. The following discussion highlights the areas where there was improvement in properties.

The grooved structure had more than a 31% decrease in specific gravity compared to the ungrooved specimens. This is sightly less than the theoretical reduction of 36% which can be computed by considering the die geometry and the initial sheet thickness. This difference is largely due to the placement of an unembossed sheet in the center of the laminates to create a symmetric layup.

Results for the rectangular grooved samples are shown in Table I. For the rectangular grooved samples, the specific bending modulus and the specific Charpy impact toughness showed significant increases. Both the all zero degree laminate as well as the 0/90 laminate showed an approximate 14% increase in specific bending modulus. This is likely due to the fact that the highest normal stresses due to bending are in the outermost zero degree direction. The Charpy impact toughness was approximately 12% higher for the all zero degree laminate than for the unembossed laminate.

The similarity in the tensile properties between the unembossed material and the all zero degree laminate was expected. This indicates that the embossed and unembossed laminates can carry an equal force per unit "actual area" when subjected to tensile loading. As expected, the tensile properties drop off when grooves are oriented at 90 ° to the applied load since

TABLE I Mechanical test results for panels with rectangular grooves

Layup	Specific gravity	Specific flexural modulus (GPa)*	Specific tensile modulus (GPa)	Specific charpy toughness (J/cm^2)
Unembossed 7 plies	1.17	1.97	1.97	32
[0/0/-/0/0]	0.80	2.23	1.92	35
[0/90/-/90/0]	0.84	2.24	1.77	–
[90/90/-/90/90]	0.80	1.82	1.34	8

*This is for bending in the zero degree direction.

TABLE II Mechanical test results for panels with hexagonal grooves

Layup	Specific flexural modulus (GPa)*	Specific tensile modulus (GPa)	Specific tensile strength (MPa)	Specific charpy toughness (J/cm^2)
Unembossed 4 plies	2.03	2.26	41.7	21.0
[0/0/0/0]	1.48	1.76	45.6	
[0/0/0/0] 10% fibers	3.96	9.99	68.9	
[0/0/90/90/] S	1.04	3.72	25.7	
[0/0/90/90] S 5% fibers	1.64	4.88	33.7	>105.0
[90/90/0/0] S	1.07	2.98	20.6	
[90/90/0/0] S 5% fibers	1.18	6.61	45.6	
[90/90/90/90]	2.00	3.22	22.2	

*This is for bending in the zero degree direction.

Figure 1 Trapezoidal die used in the microembossing process.

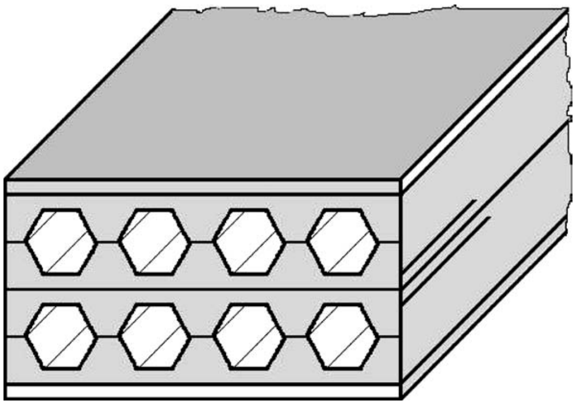

Figure 2 Laminate with hexagonal-shaped channels.

less cross-sectional area per unit weight is available for carrying the loads.

Results for the hexagonally grooved samples are shown in Table II. The hexagonal channels increased the 0° tensile specific strength, but not the 90° strength. The presence of the channels decreased the 0° tensile modulus (which is expected since we have, in effect, added "fibers" of zero stiffness). A small percentage of fibers significantly increased both the stiffness and strength of the laminate. When the hexagonal channels were placed perpendicular to the bending direction, the flexural modulus was significantly increased. When they are in the same direction as the bending, there is not an increase in flexural stiffness.

There was a significant increase in specific Charpy impact toughness when microembossing was performed. None of the hexagonally grooved microembossed laminates could be broken using a standard sized Charpy tester. Therefore the increase in specific impact toughness may be even greater than calculated. This improvement in impact toughness indicates that microembossed materials might be usable in a number of applications where a lightweight protective shield is required.

Such stiff and lightweight materials could have a number of military and civilian applications. For example, they could be used to build up a protective shield for the soldier to wear, for a lightweight helmet, and even for the inside protective shield for armored vehicles.

Future work in this area can focus on making structures with smaller and smaller channels to determine whether or not this improvement in specific mechanical properties can still be obtained. Differently shaped channels can be examined to determine which designs would simplify the polymeric manufacturing process. Mechanical testing, including tensile and fatigue testing, of polymeric laminates incorporated into composite materials and laminated to existing surfaces could then be conducted. Future work can examine the effect of creating composites with different groove geometries and with larger decreases in specific gravity. Fibers can be cemented into some of the grooves in an attempt to increase strength and toughness.

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