Effect of Fiber Misorientation on the Tensile Strength of Compression Molded Continuous Fiber Composites

P. K. MALLICK

Department of Mechanical Engineering
The University of Michigan-Dearborn
Dearborn, Michigan 48128

Resin cross-flow during compression molding of unidirectional sheet molding compound composites, such as CSMC and XMC, may cause severe misorientation of the continuous fibers in the outer layers. The extent of fiber misorientation depends on the type of molding compound, the length of cross-flow, and the location of the charge in the mold. The tensile strength is reduced in the direction of cross-flow with decreasing mold surface coverage. However, since severe fiber misorientation is generally restricted to the outer layers, increasing the number of plies improves the tensile strength to the level observed with little or no misorientation.

INTRODUCTION

The mechanical properties of unidirectional composite depend strongly upon the orientation of continuous fibers with respect to the angle of loading. When such a composite is manufactured by an automatic lay-up or even a hand lay-up technique as is done in the aerospace industry, the fiber orientation can be precisely controlled and maintained during the fabrication process. Thus, properties of the final product will not deviate much from those used in its design. Processing by compression molding is much more complex, particularly since there is very little control over the flow of material in the mold. The misorientation of longitudinal fibers due to resin flow in the transverse (cross-wise) direction is very common in compression molding of continuous fiber composites. Because of such unwarranted variations in fiber angles, a molded component may fail at a lower load than its design level which usually assumes a perfect orientation of fibers in the material.

Resin flow in compression molding is necessary not only to fill the mold, but also to expel any entrapped air or gases evolved during the curing reaction. Thus, it is common practice to cover the mold surface only partially with the uncured material, called a "charge", and then allow it to spread by the application of high pressure. In case of continuous fibers, little or no flow can take place in the longitudinal direction of fibers, and the material is forced to spread only in the cross-wise direction.

The purpose of this experimental work is to study the extent of fiber misorientation due to flow and its effect on the tensile strength of compression molded unidirectional sheet molding compound composites. The misorientation is mainly due to cross-flow of the resin in a flat mold. In many applications, cross-flow of material may take place over contoured surfaces which may cause additional misorientation.

EXPERIMENTAL

Materials

Materials studied in this work are CSMC C40-R30 obtained from Owens Corning Fiberglas and XMC-3 obtained from PPG, Inc. The CSMC sheets are produced on a sheet molding compound (SMC) machine modified to add a layer of continuous fiber rovings on top of the layer containing randomly oriented chopped fiber strands. The XMC-3 molding compound is produced by filament winding the continuous fiber strands around a large diameter mandrel. During the filament winding operation, chopped fiber strands are also sprayed on the mandrel. After the desired thickness is wound, the laminate on the mandrel is cut along its length to obtain a sheet of XMC-3.

In CSMC, continuous fibers are unidirectional, whereas, in XMC-3, continuous fibers are arranged in an X-pattern with an included angle of 10.4 degrees between them. Both materials contain approximately 40 percent by weight of continuous E-glass fibers and 30 percent by weight of randomly dispersed, 25.4 mm long, chopped E-glass fibers. The matrix in both

molding compounds for this study is a vinyl ester resin.

Molding

Flat plaques were compression molded in a 150-ton press with a 298 by 298 mm mold. A charge size of 279 by 279 mm covering 88 percent of the mold surface was used to obtain "ideal" fiber orientation. Molded plaques from this charge pattern are considered as the reference material in this work. The length of the cross-wise flow in other molded plaques was controlled by varying the width of charge in the direction of resin flow (i.e., in the cross-wise direction of fibers). By placing the charge on one side of the mold (*Fig. 1*), the material was allowed to flow in one direction only. A list of the molded plaques and their average thickness and weight is given in *Table 1*.

In case of XMC, only one ply of the material was used in the charge. Since CSMC plies were very thin, four of them were stacked together to build up a charge. The stacking sequence was (C-R)/(C-R)/(R-C)/(R-C), where C stands for continuous fiber layer and R stands for random fiber layer. A few CSMC plaques were also molded with two and six plies. The molding pressure was 9.65 MPa for all molding experiments, and, thus, the final thickness of the molded plaques was controlled by the length of the cross-wise flow. Resin burn-off test showed a uniform fiber distribution across the width of all molded plaques.

Tension Tests

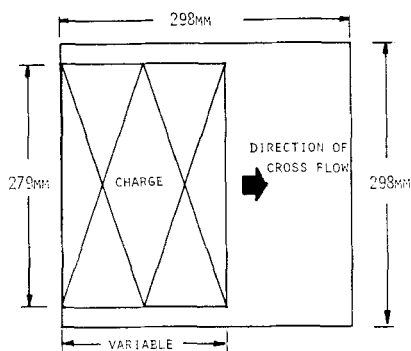Tensile specimens were cut from the middle section of the molded plaques according to the plans shown in *Fig. 2*. These specimens were 12.5 mm wide in the gage section and oriented parallel to the longitudinal direction of each plaque. Additionally, tensile specimens were obtained from reference plaques (with 88 percent mold surface coverage) at various orientations ranging from 0 to 90° with the longitudinal direction. All tension tests were performed in a Tinius Olsen universal testing machine at a crosshead speed of 5 mm/min.

RESULTS

Fiber Misorientation

Fiber orientations in the molded plaques were identified by means of continuous colored tracer fibers which were purposely included in the materials at the compounding stage (e.g., during filament winding of XMC-3, or in the SMC machine for CSMC). Local fiber angles with respect to the longitudinal direction of the molded plaques were measured with a protractor at the intersections of these tracer fibers with eleven transverse grid lines which were drawn 25.4 mm apart on each plaque. A clockwise orientation from the longitudinal direction is considered as a positive angle. Details of the fiber angle measurements are given in *Ref. 1*.

CSMC Composites

In CSMC charge before molding, the tracer fibers were parallel to each other and oriented in the longitudinal direction. In the reference plaques, molded with 88 percent mold surface coverage, the tracer fibers remained nearly parallel to each other with very little evidence of fiber misorientation. As the mold surface coverage was reduced, thereby increasing the length of cross-flow, the tracer fibers in the outer layers buckled (bowed-out) in a concave fashion in the direction of flow (*Fig. 3*). In all cases, localized buckling of the tracer fibers was observed in the outer layers throughout the entire width of the molded plaques. Depending on the length of cross-flow, local misorientation of
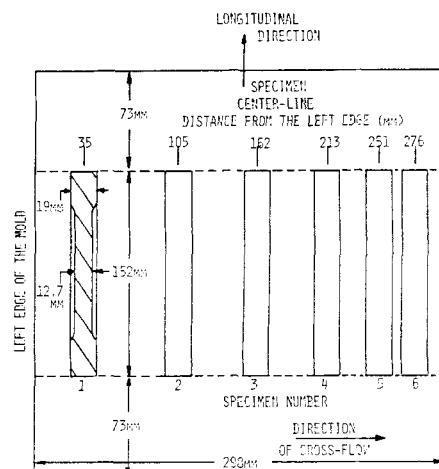

Fig. 1. *Location of charge in the mold before molding.*

Table 1. **List of Compression Molded Plaques.**

Charge Width (mm)	Mold Coverage (%)	Plaque Thickness (mm)		Plaque Weight (N)	
		CSMC	XMC-3	CSMC	XMC-3
279	88	3.83	3.24	5.92	5.22
229	72	3.16	2.84	4.81	4.50
203	64	2.81	2.55	4.32	3.97
178	56	2.45	2.18	3.78	3.47
152	48	2.11	—	3.29	—

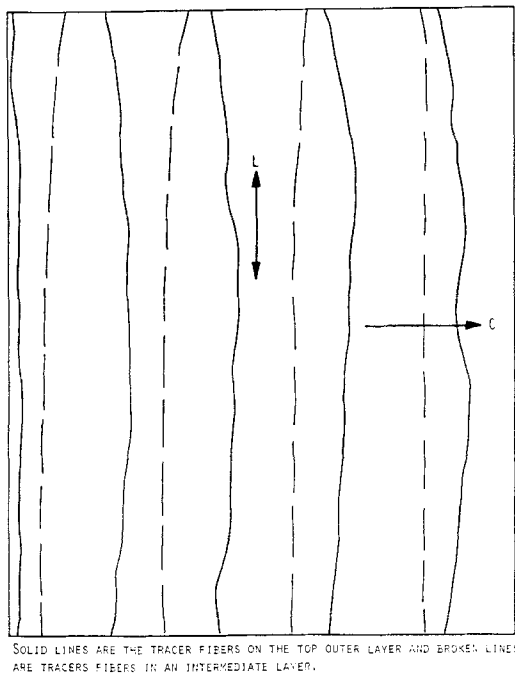Fig. 2. *Location of tensile specimens from the molded plaques.*

Fig. 3. Buckling misorientation of CSMC fibers due to cross flow in the mold (L: longitudinal direction of the mold; C: direction of cross flow).

Fig. 4. Fiber orientation angle across the width of CSMC plaques.

Table 2. Included Angles Between Intersecting Tracer Fibers in XMC-3.

Mold Coverage (%)		
88	**72**	**64**
8.64° ± 1.56°	11.23° ± 1.83°	14.1° ± 2.45°
9.98° ± 1.72°	12.33° ± 2.03°	15.3° ± 3.37°
8.72° ± 2.82°	14.53° ± 3.09°	13.3° ± 5.53°
10.52° ± 2.96°	15.63° ± 4.32°	

the continuous fibers was, at some locations, as large as 15 to 20 degrees from the longitudinal direction. An example is shown in Fig. 4. Longitudinal fibers in the intermediate layers were less affected by cross-flow as evidenced by little or no over-all buckling of the tracer fibers (which were easily visible when the molded plaques were held against white light). Local buckling effect was also much less prominent than that observed in the outer layers.

XMC Composites

In XMC-3 plaques, two different effects of cross-flow on fiber orientation were observed. First, the continuous fibers were buckled in the direction of flow. There was also some local variation of fiber angles. However, buckling misorientations of continuous XMC fibers from their original inclined positions were much less than those observed in CSMC composites. A second effect of cross-flow in XMC-3 plaques was that the included angle between the X-patterned fibers did not remain the same as that in the charge. The helix angle, set at 84.8° during the filament winding stage of XMC-3, generates an angle of 10.4° between the criss-crossed fibers. Table 2 shows the average angles between intersecting tracer fibers in various plaques. Depending upon the length of cross-flow and location in the plaque, the included angle has increased up to 16°.

Tensile Strength

Among the various mechanical properties of a unidirectional composite, tensile strength is most severely affected by the orientation of con-
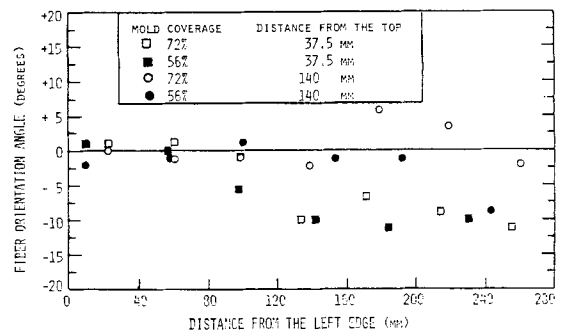
tinuous fibers with respect to the direction of loading. This is demonstrated in Fig. 5, where, fiber orientation angle, θ, represents the angle between the tensile loading direction and the longitudinal direction of fibers in reference plaques. For both CSMC and XMC composites, tensile strength is reduced with increasing fiber orientation angle. The reduction in tensile strength is greatest near $\theta = 0°$. The failure mode changes from tensile failure of fibers for values of θ less than 5° to interfiber shear at larger angles. At values of θ near 90°, failure takes place principally by the tensile rupture of the matrix.

Tensile strength variation in CSMC composites was measured for $\theta = 0°$ and 5° using specimens cut at various locations across the width of three reference plaques. Similar tests were also conducted for XMC composites at $\theta = 0°$. These results are presented in Table 3. In both composites, variation in tensile strength was random across the width and no preferential orientation effect was found. In CSMC composites, the tensile strength of a two ply material was not significantly different from that of a four ply material.

Tensile strength variations in molded plaques with partial mold surface coverages are presented in Figs. 6 to 8. The results are summarized below:

1. For four-plied CSMC composites, tensile strength decreases in the direction of cross-flow with decreasing mold surface coverage, Fig. 6. The lowest tensile strength was within the range of values measured for $\theta = 5°$ (Table 3). In the areas where the mold surface was covered, particularly near the left edge of the mold, there was a trend of increasing tensile strength with decreasing mold surface coverage. Strengthening in this area is probably due to

Table 3. Tensile Strength Variation in Reference Plaques.

Material	Thickness (mm)	Fiber Orientation	Number of Specimens	Tensile Strength (MPa)			Standard Deviation
				Maximum	Minimum	Mean	
CSMC	3.8 (4 plies)	0°	13	547.2	490	523.6	19.2
	1.8 (2 plies)	0°	14	576.6	472.7	535.5	28.5
	3.8 (4 plies)	5°	8	408.9	332.6	366.5	23.0
XMC	3.4 (1 ply)	0°	5	586.9	539.8	558.4	18.2
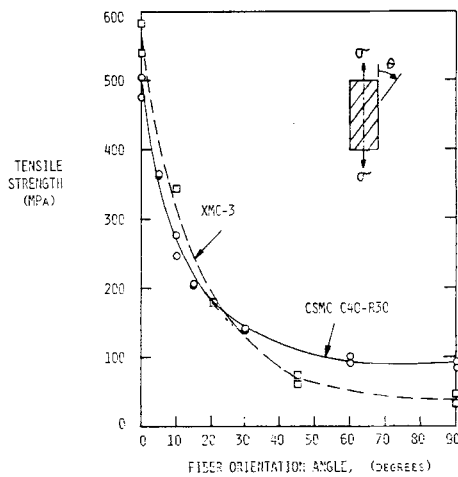
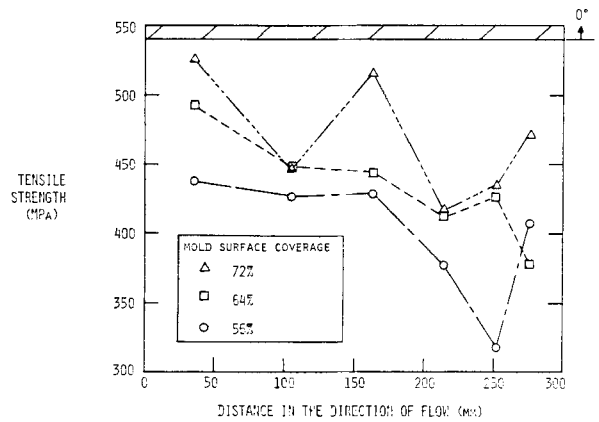Fig. 5. Tensile strength vs. fiber orientation angle.

Fig. 7. Tensile strength variation across the width of molded XMC plaques with partial mold surface coverage.
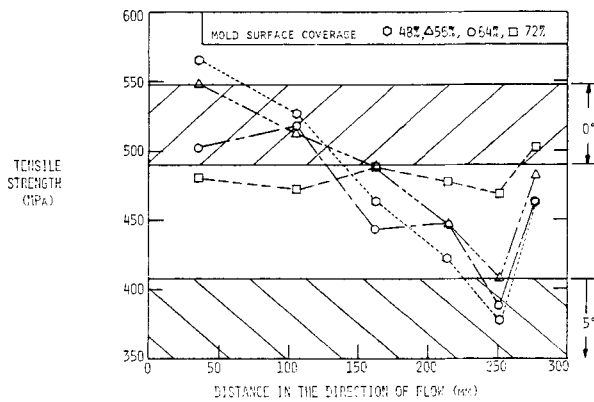

Fig. 6. Tensile strength variation across the width of molded CSMC plaques with partial mold surface coverage.
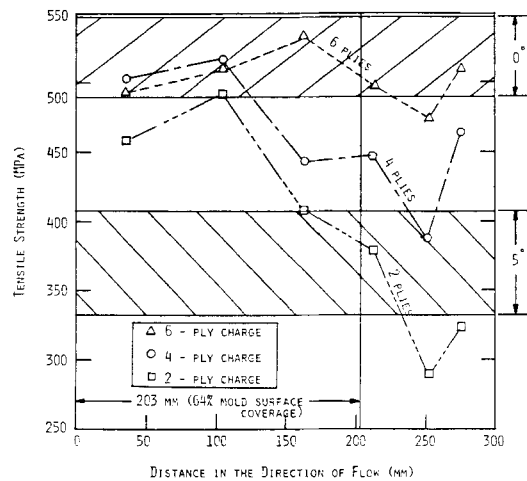

Fig. 8. Tensile strength variation in CSMC plaques with different number of plies in the charge.

reduction in irregularities in fiber orientation in the original charge as the material with less mold surface coverage was forced to flow in the transverse direction to fill the mold. Improved tensile strength observed near the right edge, i.e., end of cross-flow is due to restraightening of buckled fibers by the edge of the mold.

Results with XMC composites show a similar trend as those for CSMC composites (*Fig. 7*); however, the tensile strength, in this case, did not reach the range of values obtained for θ = 0° orientation in the reference plaques. This is partly due to an increase in the included angle between the X-patterned fibers. In a parametric

experiment on compounding variables of XMC composites (2), it was observed that as the helix angle is reduced from 85 to 82°, thus increasing the included angle between the X-patterned fibers from 10 to 16°, the tensile strength is reduced by approximately 15 percent.

2. With the same partial mold surface coverage, tensile strength of CSMC composites decreases with decreasing number of plies, *Fig. 8*. With a six-ply charge, tensile strength was similar to θ = 0° in the reference material throughout the width of the molded plaque. With two and four ply charges, tensile strength

decreased across the width in the direction of flow. In case of a two-ply charge, the lowest tensile strength was even less than the minimum observed with $\theta = 5°$. These results seem to reflect the effect of overall fiber orientation (averaged over the thickness) in the molded plaque instead of the fiber orientation in the surface layers only. Thus, even though continuous fibers in the surface layers of six-ply material are misoriented by angles ranging up to 6.73°, failure did not take place until the near 0°-fibers in the intermediate layers failed in tension. With the two-ply material, fibers in both plies are misoriented by angles ranging up to 11.14° with the loading direction. Such misorientation in fiber angles is the reason for large reduction in tensile strength observed in this plaque.

CONCLUSION

Resin cross-flow during compression molding of sheet molding compounds is necessary for mold filling as well as reducing defects due to entrapped air and gases evolved in curing reaction. In sheet molding compounds, such as CSMC and XMC, containing unidirectional continuous fibers, severe misorientation of the continuous fibers may result from resin cross-flow which is generally accomplished by partial mold surface coverage. In CSMC composites, continuous fibers buckle or bow-out in the direction of cross-flow, while in XMC composites, the included angle between the X-patterned continuous fibers is increased. The extent of fiber misorientation in the outer layers depends on the length of resin cross-flow and location in the mold.

Tensile strengths of CSMC and XMC composites depend strongly on the direction of continuous fibers with respect to the loading direction. For compression molded composites with fiber misorientations due to partial mold surface coverage, the tensile strength decreases in the direction of resin cross-flow with decreasing mold surface coverage, i.e., with increasing length of resin cross-flow. However, since severe fiber misorientations are generally restricted to outer layers, increasing the number of plies improves the tensile strength to the level observed with no misorientation.

ACKNOWLEDGMENT

REFERENCES

1. P. K. Mallick, *SPE ANTEC, Tech. Papers*, **26**, (1983).
2. Technical Service Bulletin, PPG Industries, Inc., Pittsburgh PA, 1978.