Chopped Prepregs - A Compelling Performance and Cost Alternative Material Form

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ABSTRACT

Chopped prepregs offer another material form for the composite engineers to consider. Some compelling reasons are performance parity, lower total costs, and easier transition from aluminum than continuous fiber composites.

Structure - Parts made from chopped unidirectional prepreg will yield similar performance to hand layup continuous fiber composites when knockdown effects are considered. Much of the performance gain for the chopped prepreg material form comes from its low sensitivity to traditional knock down effects. Since the chopped prepreg form has inherent flaws due to stress concentrations at the ends of the short fibers, additional property losses due to holes for attachments, moisture absorption, etc., are minimal. In addition, this chopped material form can be made into complex geometrical shapes that use geometrical stiffening to give it a competitive advantage.

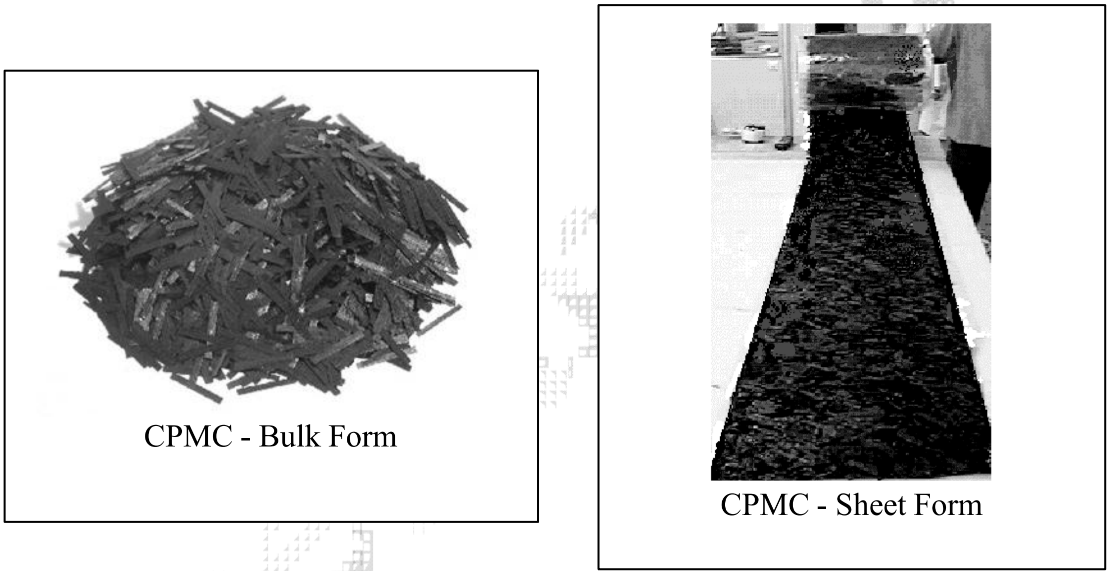
Cost – Parts made from chopped unidirectional prepreg can have an advantage over continuous fiber prepreg layups when it comes to labor content. For simple geometries it is much faster to create a random chopped fiber mat than it is to orient and vacuum bag a continuous fiber prepreg layup. In many applications the chopped prepreg form is made into a 3D part that would have required a bonded assembly operation with traditional continuous fiber composites. In order to obtain optimum chopped prepreg structural performance a preform is typically required for complex 3D shapes. The cost trade is two labor intensive continuous prepreg operations (layup/bagging and bonding), for two less demanding chopped prepreg operations (random mat fabrication and preforming). In addition, post processing requirements, such as edge trimming, drilling, insert installation, etc., can be molded to the final condition with chopped prepreg. Eliminating these operations further reduces the cost content of chopped prepreg molding compound as compared with the cost content of continuous fiber prepreg parts.

Re-engineering Aluminum – the chopped prepreg form is much better suited to aluminum replacement with composites because of its 3-D molding capabilities. It is still important to engineer some design tradeoffs to achieve the best cost and performance capabilities with the chopped prepreg, but the changes are typically minor part modifications instead of a total redesign effort. This usually results in lowering the engineering costs associated with converting an aluminum part into a composite part driven by a cost or weight savings effort.

1. INTRODUCTION

Chopped Prepreg Molding Compound (CPMC) is a relatively new material form. It is similar to molding compounds that have been made in the past using chopped resin impregnated tow. For the design and processing engineers, the advantages that chopped prepregs have are variable chip lengths and widths, resin selection flexibility, and the materials can be pre-formed into shapes, prior to molding to facilitate fabrication and improve structural performance.

Chopped prepreg can be provided in a Bulk Molding Compounds (Tencate Molding Compound) form (as loose chips) or in a Sheet Molding Compound (HexMC™) form (as a rolled up mat). Chopped prepreg in the bulk form offers more flexibility in customizing pre-forms for structural performance and has essentially no material waste. Chopped Prepreg in the sheet molding compound form reduces in-process labor content associated with making the molding compound into a mat (similar to a quasi-isotropic prepreg ply stack).



CPMC - Bulk Form

CPMC - Sheet Form

Figure 1. Chopped Prepreg Molding Compound Shown in Bulk and Sheet Form

2. APPLICATION TECHNOLOGY

2.1 Part Fabrication Requirements

Chopped prepregs are typically molded at isothermal temperatures in matched metal dies. Isothermal curing optimizes the use of capital equipment by eliminating ramped heating and cooling, typically associated with composite prepregs. Unlike prepreg autoclave molding, the use of matched metal dies provides dimensionally controlled surfaces on both sides of the part.

The essential ingredient to molding prepreg based chopped molding compounds is to apply pressure to the molding compound when the resin and fiber move as a unit. If the resin is too thick to flow or too thin to move the fiber, then the molding compound will not effectively fill the mold, resulting in a poor quality part. This is counter to autoclave processing of continuous fiber prepregs, where the lowest resin viscosity is desired so that entrapped air can be removed at low pressures. The key point - resin separation occurs when the resin viscosity is too low, causing the press to act on incompressible fibers that cannot be made to flow.

There are two methods employed to provide the correct resin viscosity for molding compounds. They are thermal thickening and chemical thickening of the resin prior to molding. Chemical thickening is done by the prepreg manufacturer, while thermal thickening can be done by either the prepreg fabricator or the part's molder. The variables for thermal thickening will be oven temperature, oven exposure time, and cure temperature. Several valid molding combinations can be discovered, but in most cases the highest viable temperature will be used in order to minimize press time. Characteristics that may limit the molding temperature are part thickness, preform installation time, and the part strength during demolding (Tg sensitivity). In all cases lower cure temperatures will help the process repeatability, but at the expense of additional press time.

For the process engineer a few additional points will likely need to be addressed. They are the potential for exothermic reactions, shelf life considerations, and degree of cure.

- Exothermic Reactions - As processing temperatures increase there is a knowledge base for autoclave processing that would suggest that isothermal molding temperatures are too high. However, for molding compounds this does not take into consideration
    - The reduced reaction capacity due to chemical or thermal resin advancement,
    - The conductive capability of the matched metal molds to remove heat quickly from the part.

- Shelf life - Is greatly extended for molding compounds. If autoclave shelf life is applied to molding compounds then material will be scrapped much earlier than is necessary. Prepreg shelf life is driven by the minimum viscosity that can be achieved so that 100 psi cure cycle can reliably remove entrapped air from the part.

  With the chemical or thermal resin advancement requirement and the 750-2000 psi molding pressure, these definitions are no longer relative. Resin advancement raises the uncured Tg above room temperature making the prepreg chip solid at storage temperatures and the resin less capable of continued advancement. While no formal studies have been conducted, excellent parts have been molded from prepreg with over 3 years of freezer storage or over one month of out-time.

- Degree of Cure – To optimize usage of capital equipment, parts are demolded as soon as they have enough strength to withstand part ejection forces. This can vary for each resin and depends on how fast the strength drops off as the Tg is exceeded. In most cases the degree of cure is significantly less than 100%. This should be considered part of the process and if a higher degree of cure is desired the process engineer can extend the cure time or complete the cure during a freestanding batch oven post cure.

2.2 Structure and Design

Traditionally molding compounds have been delegated to non-structural parts. Prepreg based molding compounds are currently being used in structural applications. The technology improvements with prepreg based mold compounds result from the usage of more advanced resin systems, more advanced fibers, precision resin control, improved fiber wet-out, straight fibers, and customized chip sizes. To illustrate this, Tencate's website identifies a variety of resin and fiber combinations used in its prepreg based molding compounds. (See Table 1 below)

Table 1. Example of the Variety of Fiber/Resin Combinations Available From Chopped Prepreg (courtesy Tencate Advanced Composite)

Product	**Description**
MS-1A	MS-1H is a high performance carbon fiber/epoxy resin compression molding system based on high modulus carbon fiber. MS-1A compression molding compound yields unparalleled stiffness and high strength. MS-1A is a qualified for space applications.
MS-1H	MS-1H is a carbon fiber/epoxy resin compression molding system using a high modulus PAN carbon fiber. This is an excellent high stiffness molding compound that has been qualified to military and commercial applications. It has excellent out time stability and processes very well in small and thin cross section parts. It is the performance alternative to the MS-4H molding compound.
MS-4H	MS-4H is a carbon fiber/epoxy resin compression molding system. This is an excellent low cost high performance carbon fiber molding compound that has been qualified to military and commercial applications. It has excellent out time stability and processes very well in medium to large heavy parts.
Cetex MC1100	TenCate Cetex MC1100 PPS is a thermoplastic based molding compound based on either standard or intermediate modulus carbon fiber. It is tough, fire retardant and capable of using very fast cycle times (less than 10-15 minutes) for forming.
Cetex MC1200	TenCate Cetex MC1200 PEEK is a thermoplastic based molding compound based on either standard or intermediate modulus carbon fiber. It is tough, fire retardant and capable of using very fast cycle times (less than 10-15 minutes) for forming.

In addition, the capability to easily mold-in ribs and gussets enables even higher structural performance to be obtained with these materials.

Designing parts with structural molding compounds should take into account

1. Part form, fit, and function requirements
2. The preform charge design (3D charge patterns are similar to prepreg layups).
3. The mold design (determines charge loading, how flow will occur, and how the part will be removed)
4. The effect of the candidate designs on manufacturing costs (complexity effect on labor and yields)

Each of these must be considered concurrently to achieve the best overall design for weight, performance, and cost. Primary consideration should be given to

- The molding approach
    - single axis or multi-axis
        - driven by performance (minimal flow) or part feature requirements
- The design of the charge patterns (plies)
    - Patterns need to provide load transitions necessary for the loads to flow around corners and from thick to thin areas, etc.
        - drives local part thickness to prevent stress concentrations
- Design the mold for preform installation and part demolding
    - The mold design should facilitate placement of a near net 3D preform in the mold
        - Preserves random fiber orientations desired for quasi-isotropic properties by minimizing flow induced fiber alignment
        - Provide room for the bulk factor of the patterns
    - Provide drafts and eliminate undercuts that will prevent demolding of the part

Additional Design Comments

- Molding is 3-dimensional, look at the charge design as a series of flattened 3D patterns
- Near net charge patterns should be used to obtain minimized flow during molding. Minimal flow reduces variation in mechanical performance
- Vertical walls - Single axis molding will force vertical walls to achieve final thickness before the mold is closed, resulting in uncontrolled material flow. There are other high flow approaches to vertical walls but the lowest flow will occur with multi-axis molding.
- Avoid abrupt thickness changes in the part design. This can cause fibers to end at a transition resulting in stress concentrations. This is particularly undesirable in a corner. Also, charge patterns are much thicker than prepreg layers, so charge pattern drop offs will be comparatively large.
    - Consider tapered transitions and generous radii
    - Use local buildups to bring a ply around a corner for a softer load transfer
- Consider the bulk factor – the bulk associated with thick areas will cause material to come under pressure and flow before thin areas

3. APPLICATION OPPORTUNITIES

3.1 Chopped Prepreg Molding Compound (CPMC) Applications

Selecting CPMC over Continuous Fiber Prepreg and Aluminum can be a cost and weight effective solution. Chopped prepreg can be used to make 3-dimensional shapes that are similar to existing aluminum parts. These parts are not easy to produce with continuous prepreg material. In addition, CPMC's compete well with continuous fiber prepregs, when attachment holes and/or other flaws are present in the part.

Holes and other flaws have been shown to have a much smaller impact on CPMC's then on continuous fiber composites. Continuous fiber composites test very high when fibers are aligned and tested between grips. There will be a significant reduction in properties when plies are constructed to provide quasi-isotropic performance (i.e. - similar performance in all directions except through the thickness). Performance of quasi-isotropic continuous fiber parts are still relatively high when compared to chopped prepreg parts until you factor in the presence of environmental and machining effects. Continuous fiber composites are sensitive to these effects as they interfere with the ability for the continuous fiber to translate load.

Environmental and machining effects are traditionally referred to as flaws because they are foreign to the pristine state of continuous fiber composites. When flaws such as attachment holes, moisture, micro-cracking, etc, are potentially present, then the designer must account for these reductions in performance by applying a knock down factor. Comparatively, CPMC's are flaw tolerant because loads already have to transition through the matrix from one chip to the next. Creating an additional flaw, such as a hole, does not create the same knock down factor that is applied to continuous fiber prepreg parts. To verify flaw tolerance, open-hole compression and no-hole compression tests were conducted on a quasi-isotropic laminate and on the chopped fiber molding compound. The same carbon/epoxy prepreg material was used in the laminate as unidirectional tape and in the molding compound as the chopped prepreg.
(See Table 2)

Table 2. Comparison Data Showing the Impact of Holes (flaws) on the Strength of CPMC and Quasi-Isotropic CFP Products

	Open Hole Compression ASTM D 6484				**No-Hole Compression ASTM D 6484 Modified**			
	Strength (MPa)		Strength (Ksi)		Strength (MPa)		Strength (Ksi)	
	CPMC	CFP	CPMC	CFP	CPMC	CFP*	CPMC	CFP*
CPMC Chopped Prepreg Molding compound	248.2	280.6	36.0	40.7	337.2	530.9	48.9	77.0
	262.0	277.9	38.0	40.3	333.0	489.5	48.3	71.0
	239.9	275.1	34.8	39.9	323.4	423.3	46.9	61.4
	275.8	284.1	40.0	41.2	328.2	600.5	47.6	87.1
	242.7	276.5	35.2	40.1	342.7	504.7	49.7	73.2
	277.9		40.3		354.4		51.4	
CFP Continuous Fiber Prepreg (Quasi - Isotropic)	298.5		43.3		288.2		41.8	
	288.2		41.8		327.5		47.5	
	271.7		39.4		355.1	*Values recorded when test was stopped	51.5	*Values recorded when test was stopped
	258.6		37.5		311.0		45.1	
	293.7		42.6		337.8		49.0	
	299.2		43.4		289.6		42.0	
	241.3		35.0		329.6		47.8	
	232.4		33.7		343.4		49.8	
	255.8		37.1		354.4		51.4	
Mean	**265.7**	**278.8**	**38.5**	**40.4**	**330.4**	**509.8**	**47.9**	**73.9**
S Deviation	**22.6**	**3.6**	**3.3**	**0.5**	**20.8**	**64.4**	**3.0**	**9.3**
COVariance	**8.5%**	**1.3%**	**8.5%**	**1.3%**	**6.3%**	**12.6%**	**6.3%**	**12.6%**

Chopped Prepreg MC - Strength			
without hole	w/Hole	% drop	
330.4	265.7	**19.6%**	MPa
47.9	38.5	**19.6%**	Ksi

Continuous Fiber Prepreg		
without hole	w/Hole	% drop
509.8*	278.8	**> 45.3%**
73.9*	40.4	**> 45.3%**

In addition to the effect of holes, it has been observed (data not available) that hot/wet properties will have a similar effect on the traditional prepreg test specimens making the two material forms even more equivalent when both holes and environmental conditions are present. The simplistic explanation for this difference is that the chopped prepreg has inherent flaws that mitigate the effect of additional flaws, such as holes, moisture, and heat. As the data indicates, the performance hit is approximately 20% for the molding compound and is greater than 45% for the prepreg. Due to current design rules there is a tendency to apply the same knock down factor to molding compounds and prepregs. With this new knowledge, chopped prepreg molding compounds can be considered with lower knock down factors that will open up new opportunities for this material form.

Another test that gives near equivalent results between the two material forms is Bearing Strength. This is another flaw driven test that indicates Chopped Prepreg Molding compound Performance in relation to Quasi-Isotropic Continuous Fiber Prepreg Composites.

Table 3. Bearing Strength Comparison

Bearing Response ASTM D 5961 (Method B, Supported, Tension)				
	Strength (MPa)		Strength (Ksi)	
	CPMC	CFP	CPMC	CFP
CPMC Chopped Prepreg Molding compound	787.6	946.7	114.2	137.3
	1021.6	943.1	148.2	136.8
	914.9	970.2	132.7	140.7
	892.8	887.6	129.5	128.7
	901.1	920.2	130.7	133.5
CFP Continuous Fiber Prepreg (Quasi - Isotropic)	898.1		130.3	
	816.6		118.4	
	783.2		113.6	
	916.0		132.9	
	784.2		113.7	
	839.6		121.8	
	902.2		130.9	
	744.9		108.0	
	835.8		121.2	
	839.8		121.8	
Mean	**858.6**	**933.6**	**124.5**	**135.4**
S Deviation	**71.5**	**31.2**	**10.4**	**4.5**
COVariance	**8.3%**	**3.3%**	**8.3%**	**3.3%**

Bearing Strength Comparision				
	Minimum	% reduction	Mean	% reduction
	(Mpa)		(Mpa)	
CFP	887.6	16%	933.6	8%
CPMC	744.9		858.6	
	(Ksi)		(Ksi)	
CFP	128.7	16%	135.4	8%
CPMC	108.0		124.5	

The data presented is intended to provide the composite design engineer with opportunities that will enable consideration for using a chopped prepreg material form. If the part's performance with continuous fibers will be subjected to knock down factors for holes and/or environmental conditions there maybe an opportunity to reduce total part costs and obtain the same weight savings offered with conventional prepreg composites.

3.2 Substituting Chopped Prepreg Molding Compound For Aluminum

Carbon fiber composites can provide up to a 45% weight savings when a 1:1 substitution is made for aluminum. In addition, CPMC's can be easily formed into attachments, etc. that interface with other carbon parts, thereby eliminating the galvanic reaction concern that occur with aluminum parts. As shown below, CPMC’s material properties compare well with 6061 T6 aluminum properties.

Table 4. Mechanical Test Data Comparison of CPMC and Aluminum

Material	Tensile				Compression				Shear	
	Strength		Modulus		Strength		Modulus		Strength	
	MPa	Ksi	GPa	MSI	MPa	Ksi	GPa	MSI	MPa	Ksi
CPMC (MS4H-1")	302.0	43.8	42.7	6.2	330.3	47.9	50.3	7.3	177.9	25.8
6061-T6	290.0	42.0	68.9	10.0	290.0	42.0	68.9	10.0	186.0	27.0
7075-T6	524.0	76.0	71.7	10.4	524.0	76.0	71.7	10.4	317.0	46.0

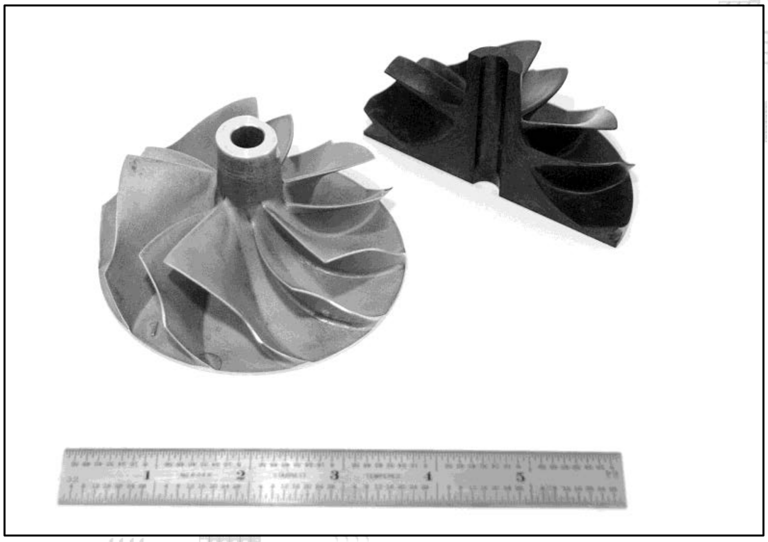


Figure 3. CPMC Substitution For Aluminum
(Courtesy Tencate – CCS Composites)

For CPMC it can be easy to make this material substitution with a few changes. Areas to be reviewed include

1. Thickness requirements (very thin parts (<0.045”) require additional process development)
2. Part load paths requirements - design adjustments that address that are quasi-isotropic in nature rather than isotropic. (corner wraps, thickness blends, etc)
3. Thread Requirements -Ensure molded or bonded in inserts can be used in those areas (boss maybe required)
4. Stiffness requirements – Use geometry for local stiffening (gussets, etc)
5. Undercuts requirements in relation to the molding direction. A common machined feature in aluminum
6. Drafts requirements for part removal. Aluminum machined parts will not have drafted surfaces in most cases

As a final thought, consider giving up some weight savings to reduce tooling costs, reduce fabrication costs, and improve process repeatability. In many cases, after making adjustments to address performance and cost, the weight savings will be in the 25-35% range. Beyond weight savings and galvanic reaction advantages, using a carbon chopped prepreg molding compounds in place of aluminum can provide radio translucency and improved fatigue performance.

3.3 Chopped Prepreg Molding Compound - Application Examples

Figure 4. Representative Chopped Prepreg Molding Compound Parts (Courtesy TenCate – CCS Composites)

4. CONCLUSION

As a new material form, chopped prepreg molding compounds (CPMC) have compelling advantages to offer over continuous fiber prepreg and aluminum, in certain applications. Engineering considerations were discussed for both the design and fabrication of chopped prepreg based parts. The applications for competition with continuous fiber prepreg part designs occur when flaw conditions are added, such as attachment holes and environmental conditions. For aluminum, CPMCs offer a more direct conversion due to their 3D molding capabilities. In addition, opportunities exist to replace 6061-T6 or similar aluminum parts on a 1:1 strength basis and achieve a very high weight savings. As composites gain momentum in primary structural applications there is a real need to replace aluminum interfacing components with materials that do not create a galvanic reaction with carbon. The 3D geometry and high structural requirements make Chopped Prepreg Molding Compounds a good candidate for meeting these demands.

Authored by Jack D. Fudge PE

5. REFERENCES

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