COMPRESSION MOLDED BILLET: ADVANTAGES AND USAGES

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ABSTRACT

The term "billet' immediately brings to mind metallic isotropic materials. The metals industry commonly produces blocks, sheets and bars of material as a raw material from which simple and complex parts are machined into life. It is one of the least efficient and most costly of all metallic part fabrication processes. Yet, there is still a need for the machine from billet method when either part geometries or low part quantities require it. With the advent of molded plastic and composite parts, the need for doing a "hog-out" machining process on a billet of material to fabricate parts had become antiquated, or at best inefficient and costly. But, just like for metallic hog-outs, there is still a niche for the same process with composite materials. Whenever the geometry is very complex, the number of parts is low or many geometry changes are anticipated in development, it can and does make sense to consider machining composite parts from billet stock. Compression molding of discontinuous long fiber (DLF) billet stock offers an added advantage in that the billet material can be manufactured efficiently and at lower costs when compared to continuous fiber laminated billet material. But, there are some limitations when using DLF billet stock that need to be taken into consideration when substituting this method of part fabrication for near net compression molding or hand layup.

1. INTRODUCTION

Compression molding of discontinuous long fiber (DLF) composite materials has been an option for fabricating lightweight parts for decades. Compression molding allows for complex features such as ribs, bosses, pockets, and extreme thickness changes to be incorporated into the manufacture of advanced composite components that are otherwise prohibitive through typical layup techniques. However, fabrication of these parts require matched metal tools that are capable of handling high forming pressures. Tooling lead times and costs are sometimes limiting factors, especially when just a few prototype or production units are required. It is therefore advantageous to have the ability to machine complex components from a billet of DLF composite.

DLF can be molded using standard size tooling to form plates of billet stock to thickness to as much as 76mm (3.0 in.) (current stock tooling limitation at TenCate). As is typical for compression molded parts using DLF bulk molding compounds, the molded billet/plate will result in a near quasi isotropic set of material properties in the plane of the plate and will give through-the-thickness properties that are slightly higher than that of continuous fiber laminated composites. An advantage over a continuous fiber laminated billet/plate is that the DLF billet can be formed rapidly without the need for long layup times and autoclave cures.

Composite billets that are compression molded from DLF are used to create many types of composite parts. A common use is to machine "pucks" or other flat shapes that are then used as inserts in honeycomb sandwich panels, between the face sheets, to establish hard points for mounts and attachments. Relative to prototypes, complex pieces are machined from carbon fiber/epoxy billet stock to quickly produce representative compression molded components for evaluation and testing. One such component is an aerospace part that includes very close tolerance features, extreme thickness changes, bosses and pockets. Ultimately, the part will be fully compression molded, but the billet machined prototype meets the customer's short lead time requirement. Short run production units also make viable candidates for using billet stock and machining the parts.

On a coupon level, testing has been done to compare the as-molded to the as-machined material properties and strengths. For molded parts the fibers have a tendency to line up at the edges of the parts. This produces a degree of anisotropy that biases the properties and strengths in the edge directions. Also, since fibers tend to laminate in-plane rather than orient themselves through the thickness, this inherently limits the application of billet machined parts to structures that have relatively low out-of-plane loads.

2. COMPRESSION MOLDING DEFINED

Compression molding is a fabrication process for producing long fiber filled composite parts that have a high degree of geometric complexity. The process involves placing a bulk molding compound (BMC) into a matched metal tool, applying heat to the tool, bringing the cavity and core halves of the tool together in a press and compressing the BMC at high pressure such that it fills all the cavities of the tool. The BMC is more fully explained in the next section. The resulting part is either net shaped or near net shaped. Figure 1 shows the basic process.

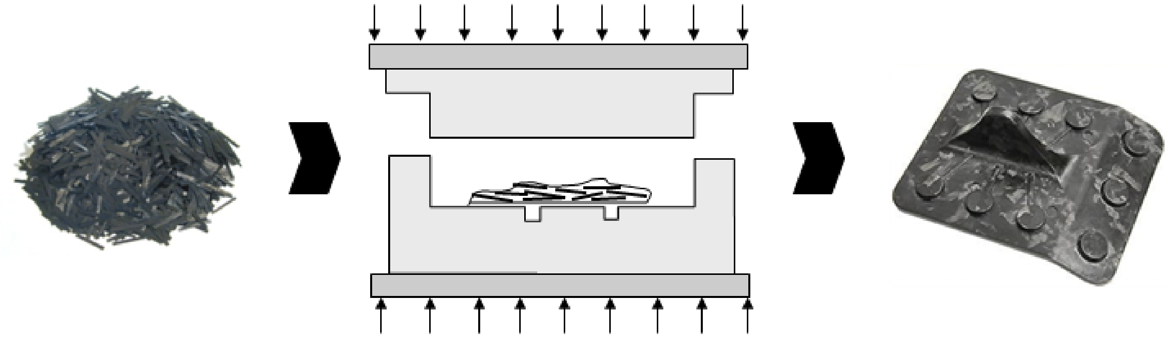

Figure 1. Basic Compression Molding Process

There are several reasons to use compression molding for part fabrication, rather than other composite part fabrication processes.

1. Complex parts can be molded that would be very difficult to fabricate otherwise. Think in terms of the level of complexity possible for injection molded parts. Compression molded parts can approach this level of complexity. But, compression molded parts are stronger and stiffer than injection molded parts due to the log fibers. However, tiny thin features

common to injection moldings are not best applied to compression molding due to the large and long fibers of compression molding needing to fill these features.

2. Metallic parts like brackets and fittings can be difficult to fabricate with laminated composites, but the benefits of light weight composites are still desired. Compression molding is a natural progression for metal part conversion to composite, especially if the metal part geometry cannot change drastically to meet the limitations of layup fabrication methods.
3. Molding lends itself to easy incorporation of inserts, pad-ups and ribs in the net molded part. These add stiffness, strength and reduce post processing work.
4. Dimensional control and part stability are inherent results of a compression molded part. The closed volume, matched metal tooling delivers repeatable dimensions from part to part.
5. High production volume parts are a good fit for compression molding as multiple cavity tools can be used and resident time in the tool is only 15 minutes, depending upon the resin system used.

3. MATERIAL AND PROPERTIES

A broad definition of compression molding would include the use of material forms such as sheet molding compounds, continuous fiber fabrics, uni tape and even short discontinuous fiber composites. The applications here for billet, however, are focused on discontinuous long fiber bulk molding compounds.

BMCs for compression molding at TenCate/CCS are essentially chopped uni prereg tape. Figure 2 shows a typical sample of carbon fiber BMC. Producing the BMC begins with using unidirectional prepreg tape in either thermoset or thermoplastic matrices.

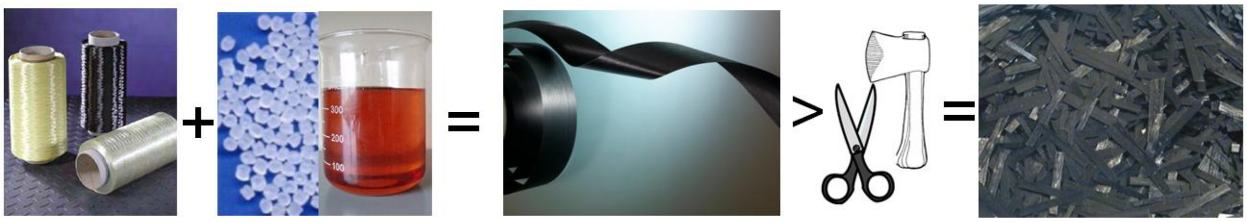

Figure 2. Bulk Molding Compound Preparation

While the thermoplastic matrices are exactly the same as off-the-shelf thermoplastic uni tape, the thermoset matrices have been modified from the off-the-shelf standard uni tape so as to yield a prescribed viscosity at cure temperatures that is neither to low nor too high for compression molding. The unidirectional tapes are then simply processed through a slitter and cutter that slits the BMC to the desired width and cuts it to the desired length. Fiber lengths range from 6.4mm to 50.8mm (0.25 inch to 2.0 inch). The most common length that gives a good balance between high strength. low material property standard deviation, and formability is 25.4mm (1.0 inch). Shorter fibers like 6.3mm (0.25 inch) can be used in parts that have a high degree of intricate detail so that fibers more easily migrate into the features. While the BMC fiber width can be such that the material is a perfect square, or a chip, the more common width is 3.2mm (0.125 inch). In addition to BMCs using epoxy, PEEK, PPS, PEI, and PEKK matrices, other BMCs from sources outside of TenCate/CCS can be used, particularly those that are qualified to aerospace prime specifications including systems like BMI, cyanate esters and phenolics.

In parts where the BMC can be more or less placed into all of the features in the mold, like billet stock, the fiber orientations for the BMC take on a near quasi-isotropic random layup in the plane of the billet. Table 1 gives typical properties for this random layup. Since the main use of compression molded parts is for conversion from metals to composites, for weight savings, the following table shows a comparison of standard modulus carbon fiber/epoxy BMC (MS-4H) to various metals. Also shown, for comparison, are properties and strengths for a quasi-isotropic continuous fiber carbon fiber/epoxy composite (55% fiber content by volume). From this is it easy to see that compression molded BMC properties from billet are lower, in general, than for continuous fiber laminates. Therefore, conversion to compression molding from continuous fiber lamination must be driven by added part complexity or high volume production requirements.

Table 1. Material Property Comparison

Property	**6061-T6 Aluminum**	**3AL-2.5V Titanium**	**CF/Ep BMC MS-4H** (1)	**CF/Ep Quasi Uni Lamina Layup**
Resin Content (Wr)	na	na	43%	37%
Tensile Strength, Mpa (ksi)	303 (44)	689 (100)	302.0 (43.8)	675 (98.2)
Tensile Modulus, GPa (Msi)	69 (10)	107 (15.5)	42.7 (6.2)	47.7 (6.92)
Flexural Strength, Mpa (ksi)	303 (44)	689 (100)	750.1 (108.8)	-
Flexural Modulus, GPa (Msi)	69 (10)	107 (15.5)	64.1 (9.3)	49.7 (7.2)
Compression Strength, Mpa (ksi)	303 (44)	689 (100)	330.3 (47.9)	549 (79.6)
Compression Modulus, GPa (Msi)	70 (10.2)	109 (15.8)	50.3 (7.3)	44.4 (6.43)
Open Hole Comp. Str., Mpa (ksi)	-	-	265.4 (38.5)	340 (49.3)

(1) Based upon molded coupon specimens, not machined. See limitations section below.

4. BENEFITS OF BILLET

For high volume production, machining parts from billet makes no sense. The costs will be higher, the production rates lower and the performance possibly decreased. But, there are situations where it does make good sense to fabricate parts from billet. Here are six great reasons to machine parts from billet stock, with the associated benefits.

1. **Avoid High Tooling Costs**: Compression molded parts require matched metal tooling, usually using hardened tooling steels, because of the high 138 bar (2,000 psi) pressures required for molding. Depending upon part size and complexity, mold costs can easily soar from $20k to $80k. Parts machined from billet have a tooling cost equal to zero!

2. **Prototype Parts**: Compression molding a net shaped part requires a mold. If all that is needed is one or two prototype parts fabricated in short order then the lead time and cost of a mold can be avoided.

3. **Part Iterations During Development**: This goes along with the prototype advantage. If several iterations of a design are going to be required because of possible design changes prior to production, buying multiple molds would be expensive. Machined parts from billet will save costs and time.

4. **Low Volume Production**: For part counts in the 10s it could be beneficial, to save costs, to avoid getting mold tooling fabricated and amortized into the unit costs.

5. **Short Lead Time**: As motioned above, avoiding the 10 to 16 week lead times, typical for compression molding tooling, is avoided and parts can be quickly machined from billet stock.

6. **Lower Cost Compared to Laminated Billet**: Billet can also be fabricated using continuous fiber lamina and autoclave cure. However, for thick laminates, DLF BMCs can be compression molded with lower labor and processing costs.

5. BILLET MOLDING AND PART MACHINING

The process for molding billet is the same as for molding net shaped parts. BMC material is pre weighed to equal the exact volume for the desired billet length, width and thickness. The BMC flakes are sprinkled onto a pattern board that has the shape of the tool cavity. The pattern board is placed into an oven and the BMC is heated, compacted by hand and then placed into the cavity of the mold. This pre-forming process is repeated until all of the material has been placed into the cavity. This application of the BMC onto the pattern boards results in a near quasi-isotropic/random fiber orientation in the plane of the billet plate (Figure 3). There is only a slight alignment of fibers out-of-plane, in general, of only 15° for 25mm (1.0 in.) long fibers, resulting in a layup having a high degree of lamination. When all of the material has been placed into the cavity, the core is pressed into the cavity at low pressure and held for several minutes, heating the material with he preheated core and cavity. Full pressure is applied and held for 15 to 30 minutes as the material consolidates and cures.

Figure 3. Stacking of BMC through-the-thickness
(photograph of unpolished specimen).

During the compression molding process the quasi-isotropic oriented fibers experience very little movement, and for the most part, retain the orientation that was set in the pre-forming and mold filling operation. The exception to this is at the edges of the billet. Here the cavity is not completely filled with the BMC during the mold filling process. There may be slight gaps and voids here where fibers terminate at the cavity walls. As pressure is applied, and as the resin liquefies, fibers are moved into these unfilled edge regions. This movement causes some re-alignment of the fibers. Particularly, fibers that were nearly aligned parallel to the cavity edge tend to now align with the edge, and there are many in this alignment due to the fact that fibers tend to align with the edges anyway. Some of the fibers in the pre-form are aligned perpendicular to the edge. Some of these will move to be less perpendicular and some will bend and fold to have some alignment through-the-thickness as the fiber impinges on the edge of the tool. It can be seen, however, that for most of the part, the fibers will retain their near quasi-isotropic, in-plane, laminated alignment. Figure 4 is a photo of the as molded surface of a billet compared to a machined surface. The machined image reveals some of the out-of-plane characteristics.

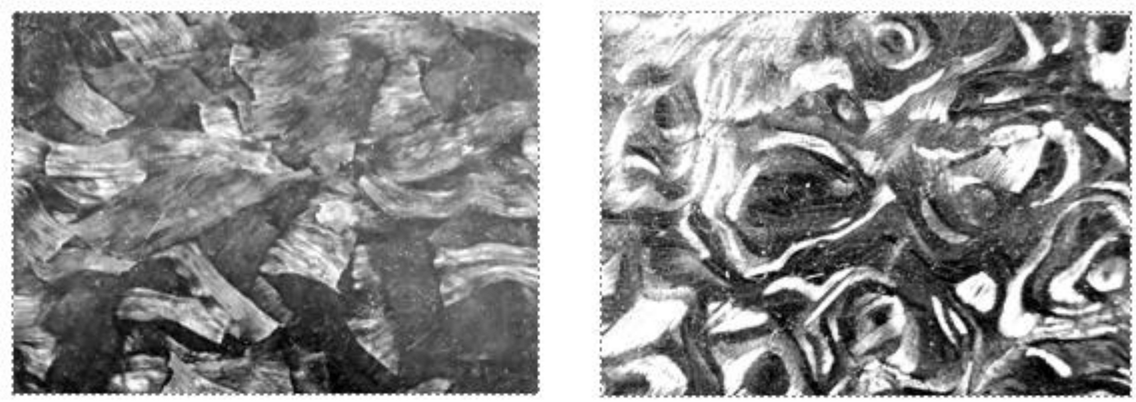

Figure 4. Surface of Billet as Molded vs. Machined

Once molded, the billet is then machined to produce the part (figure 5)

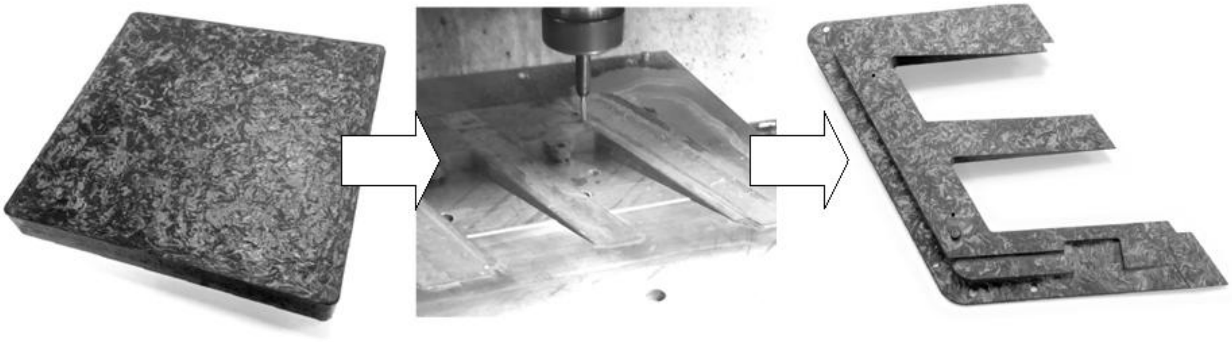

Figure 5. Machined Part From Billet

6. LIMITATIONS

There are two inherent effects that result in property and strength differences between a molded part and a part machined from billet.

1. Fiber alignment that naturally occurs along the edges of the part during net molding tend to boost the properties and strength in this region of the part. This produces a degree of anisotropy that biases the properties and strengths parallel to the edge directions. This is not so in a part machined from billet since everything is machined away. There will be slight reductions in properties and strengths for the billet when compared to that of molded coupons in Table 1. For example, compression modulus is reduced by 23% and compression strength by 18%. However, since these reductions are based upon test coupons that are only a little wider than the fibers are long, substantial edge effects will affect the results is a way that degrades the material performance more than would be seen in machined from billet structure.
2. Figure 6 illustrates that for molded parts the fiber lamination follows the contour of the part, as is usually the desired outcome. But, for a part machined from billet the lamination will be parallel to the plane of the billet/plate and not the part geometry. For the part illustrated, this results in one leg of the part that has fiber that does not follow the part contour. Since lamination gives lower strength in the out-of-plane direction, this effect may not be advantageous to the part performance, and will not be representative of the same part if it were molded.

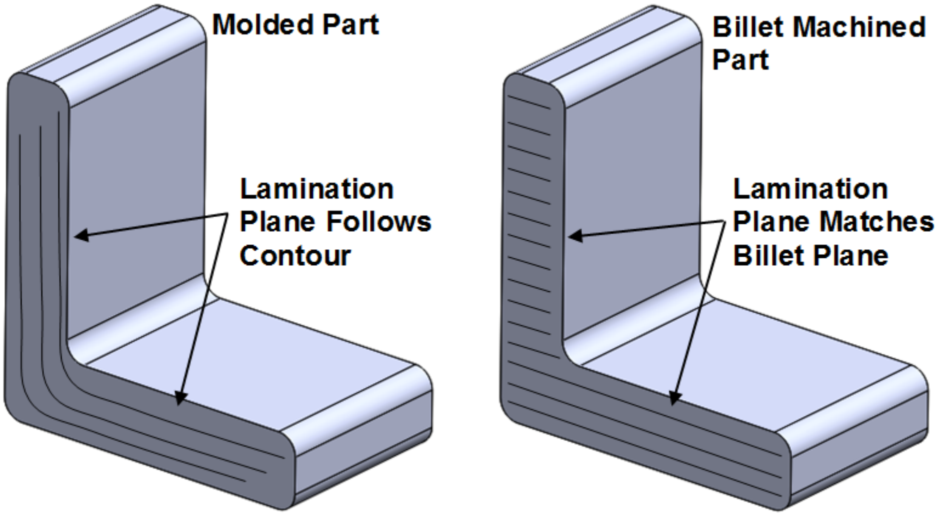

Figure 6. Lamination Plane for Molded vs. Machined from Billet

While different size billets are possible with the acquisition of additional billet compression molding tools, the current billet size limitations at TenCate/CCS are blocks up to 76mm (3 in.) in thickness with dimensions of either 15 x 15 cm, 20 x 25 cm, 30.5 x 30.5 cm, 30.5 x 45.7 cm, or 35.6 x 71 cm (6 in. x 6 in., 8 x 10, 12 x 12, 18 x18, or 14 x 28).

7. USES AND APPLICATIONS

Uses for billet are virtually unlimited whenever it makes sense to machine a part from a billet. Several applications are already in use and are shown in the following figures:

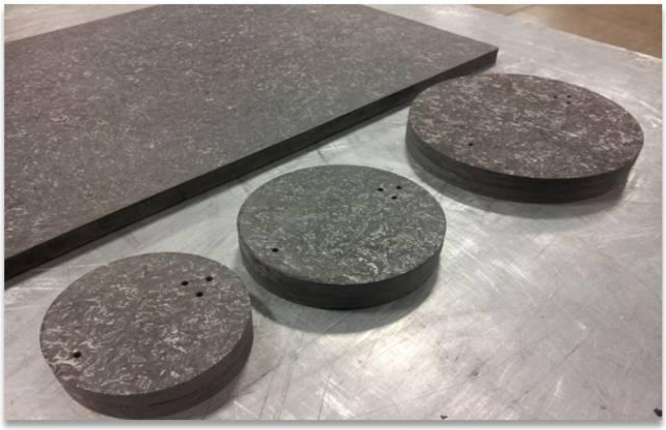

Figure 7 Hard Point Inserts for Honeycomb Panels

Figure 8 Lightweight Spacers

Figure 9 Aerospace Flight Article

8. CONCLUSIONS

Compression molded DLF composite billet stock can be useful and advantageous in the fabrication, via machining, of certain part applications that require short lead times, design iterations or low production quantities. Limitations include out-of-plane lamination effects that do not represent fiber alignment that would be produced in a net shaped compression molded part. Applications are numerous and are limited only to what can be physically machined.

9. REFERENCES

1. Howell, D.., et al, *Compression Molding of Long Chopped Fiber Thermoplastic Composites*, CAMX 2014, Orlando, FL.
2. AGATE LAMINATE MATERIAL QUALIFICATION, REPORT NO.: TCQAL-T-1026, Section 3.1, p. 35
3. Data Sheet, *MS-4H BMC*, MS-4H_DS_042913