Part and Mold Design Guidelines for the High Volume Compression Molding of Carbon Fiber Reinforced Epoxy

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Abstract

The objective of this paper is to discuss unique part and mold design requirements for high volume, cost competitive compression molding of carbon fiber reinforced epoxy (CF/E) uni-directional prepregs (UD). The typical part and mold design for compression molding of chopped fiberglass reinforced polyester sheet molding compound (SMC) will be used for comparison. Information that can be used as a design and processing guide for composites engineers involved with the development of high stiffness and strength CF/E for application in the transportation industry will be shared.

Mold Design

Finding relevant reference material on the topic of compression molding pre-impregnated materials was difficult. The best reference book discovered was "Compression and Transfer Moulding of Plastics" by J. Butler, published in 1959.[1] While rather old, the book provides an excellent resource and does a fairly good job explaining what is called a "Flash Mold", shown in Figure 1.

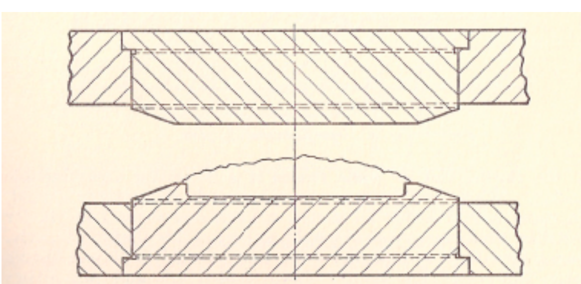

Figure 1, Typical Flash Type Compression Mold

The important features of a Flash Type mold to recognize are: The unconsolidated material has been piled up in the center of the cavity, there is a landed area entirely around the perimeter of the cavity, when the mold is closed the excess resin will be forced out of the cavity until the plug contacts the cavity land. There is clearance around the parting line for the excess resin to flow.

1. J. Butler, Compression and Transfer Moulding of Plastics, 1959, The Plastics Institute, Iliffe & Son Limited.

The design engineer must be aware of the amount of tonnage to be applied, because once the mold has closed all of that pressure will be carried by the metal area (landed area) around the perimeter of the cavity. When fiberglass (or CF) reinforcement is employed these exceptionally hard and abrasive materials will coin the landed area of the die and eventually cause significant damage to the cavity. It is not unusual for the coining of the cavity metal to cause die lock, interfering with extraction of the part from the cavity causing damage to the part at the parting line.

The Flash Type mold design shown in Figure 1 was improved by the addition of a puddle vent outboard around the perimeter of the land. The land between cavity and this vent pool is relieved by about 0.25mm (0.010") permitting the excess resin to flow and allowing some minor reinforcement to move into the landed area. Hardened steel mold stop pads are added around the perimeter of the mold, typically at or very near the corner guide pins.

A Flash Type mold works very well for materials with extremely low bulk factors. When reviewing Figure 1, it is easy to understand the limitation of a flash mold when materials with higher bulk factors are used. The bulk factor for a typical pre-consolidated CF/E tailored blank is normally very low. For the sake of this investigation, I am assuming that we will be molding laminate between 0.80 mm and 3.00 mm thick. The pre-impregnated material as received will have a bulk factor of approximately 1.6. A 0.80 mm molded part will have a non-consolidated blank thickness of approximately 1.28 mm; the 3.0 mm blank thickness will be approximately 4.8 mm.

When compression molding a CF/E pre-impregnated material it is very important to remember that the amount of extra/excess resin has been minimized. Optimally, the amount of resin squeeze out realized will be nearly non-existent. The normal molding pressures utilized for compression molding of reinforced press molding grades of epoxies is 250-300 psi. Care must be taken not to apply that amount of pressure too quickly because when the dry to the touch epoxy resin melts, the initial viscosity drop is significant. Therefore the resin will immediately begin to flow and it is very easy to force too much resin out of the reinforcement in the laminate.

The normal process employed when press-molding epoxy is to close the mold partially or just until the plug and cavity come into contact with the blank/charge. This is referred to as the KISS. This KISS in the manufacturing process is also referred to as the dwell. The amount of dwell time is derived from the state of cure of the epoxy resin and the viscosity rise. If pressure is applied too quickly the lower viscosity resin will squirt/ flow very rapidly and conversely if the pressure is applied too late the viscosity of the resin may be too high for adequate flow to occur at the selected molding tonnage. It is important to remember that the state of cure for an epoxy resin is directly related to the resin (melt) viscosity. Epoxy resin during the polymerization process behaves very much like a thermoplastic resin up to an extremely high molecular weight.

The Printed Circuit Board (PCB) compression molding process occasionally utilizes vacuum during the pressing operation. The application of vacuum aids significantly in the extraction of trapped air and residual reactive volatiles, specifically entrained water. The PCB industry uses many water immersion processes required to etch, strip and plate the copper that is adhered to the partially cured epoxy laminate. The PCB industry commonly dries a stack of laminations for a period of time in an oven at 250^{o}F, the epoxy pre-impregnated material is not completely cured, it will melt and flow when placed into the hot compression mold and then pressed.

The application of vacuum is typically achieved by placing a vacuum chamber entirely around the press platens and mold. I have never seen or read about an epoxy pre-impregnated material being vacuum press molded in another manner. SMC molding on the other hand also applies a vacuum during the molding process whenever in-mold coating is required.

SMC Mold Design

Sheet Molding Compound (SMC) molding requires the use of a telescoping shear edge mold design, shown in Figure 2[2]. The vertical parting line is typically utilized for materials with higher bulk factors. SMC is typically cut, stacked in rectangular charges and placed in the center of the mold cavity (or core). It is not uncommon for the SMC charge to engage the closing mold halves before the shear edges have engaged. The need for mold position control during the press closing process must be guided carefully in order to prevent damage to the vertical shear edge or parting line.

2. SMC Design Manual, Exterior Panels, 1991, The Composites Institute of the Society of Plastics Industry, Inc.

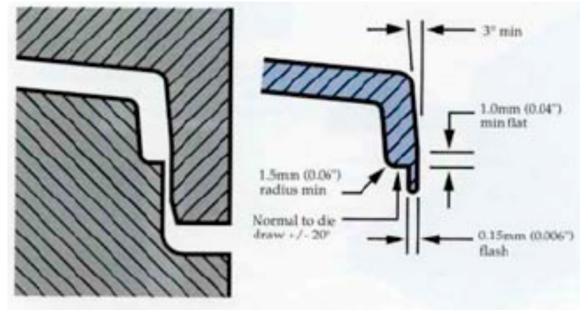

Figure 2, Typical SMC Compression Mold, Shear Edge

Molding pressures in a typical SMC pressing operation can be expected to be above 1000 psi and regularly are 2000 psi (1 ton per square inch). This tonnage is required to make the chopped fiber reinforced material flow. The high molding pressure is also required to keep the reactive monomer (styrene resin) in solution during the cure process. The typical molding temperature of 300^{o}F is well above the boiling temperature of the styrene resin.

The internal pressures realized during the SMC compression molding process are quite significant. This engineer believes that the cavity dimension shown in Figure 2 is "probably" inadequate. It is not unusual for the in-mold pressures to deflect and eventually damage a cavity at the telescoping parting line. The amount of steel shown in Figure 2 is too thin; the cavity will bend and deflect under molding tonnage opening the parting line, creating additional flash and in worst-case conditions result in large amounts of SMC flowing out of the mold. This loss of molding pressure results in exceptionally poor quality moldings and was quite common when this engineer worked a SMC and BMC press line.

Well-designed SMC compression molds will provide fairly thick steel cross sections outside of the cavity. It is very common for a mold designer to utilize wear and guide plates in areas of long straight shear edges, these are used to reinforce and stiffen a cavity wall.

Vacuum is occasionally utilized during the SMC compression molding process. When the product requires a Class-A surface finish and will be painted in a normal high volume automotive assembly plant, in-mold coating is injected on the Class-A side of the part.

The In-Mold Coating process, Figure 3, benefits from the application of vacuum prior to the high-pressure injection of the resin. Usually, the mold has been carefully opened 0.010", parallelism controlled and then prior to injection a vacuum of greater than 20 in-hg is very quickly applied. This evacuates trapped air and volatiles aiding the IMC flow and helping insure adequate fill of the cavity.

The In-Mold Coating Process
For molds and production facilities equipped for IMC, the following process occurs.

After an SMC panel is sufficiently cured during the molding cycle, molding pressures are reduced to allow the high-pressure injection of IMC. In some cases the mold is actually opened a small amount. After the material enters the mold (on the Class "A" surface side of the part) pressures are increased again to force the IMC into the extremities and higher elevations of the mold cavity.

Figure 3, In-Mold Coating Process (IMC)

I've seen these types of molds built and product produced, but I have been unable to secure reference material providing adequate design information. The parting line of a typical SMC mold equipped for IMC is best described as having two telescoping shear edges. The main shear edge contains the SMC molding material and has an average engagement of ¾ -1 inch. This shear edge is metal (core) to case flame hardened metal (cavity) with a flash gap of approximately 0.005". Out-board of the main shear edge is another vertical parting line. The IMC vacuum seal engages about ½-1" more than the main shear edge. There is a high temperature elastomeric O-ring/seal embedded in the plug or cavity side of the mold. The vacuum line connected to the mold is normally a rather significant diameter reinforced neoprene type hose (2-4" OD) providing for the exceptionally rapid "draw-down" application of high vacuum.

CF/E Mold Design Discussion

This design engineer believes that the optimum compression mold design for producing CF/E high performance products will utilize features from both Flash and Telescoping Shear Edge molds.

A flash type parting line will be utilized with a half-radius puddle vent entirely around the cavity. The flash line (land) will be about ½-1 inch with a 0.005" clearance. An IMC type of vertical parting line will be used in-order to draw high vacuum during the KISS (or Dwell) part of the molding cycle.

This final compression molding cycle will be utilized without the benefit of external tabs or locating features. This engineer proposes to employ the standard metal forming part locating standard of a 1" diameter 4-way datum hole and a 1" X 1.5" oval 2-way datum hole. The SMC compression molding industry has a difficult time molding tight tolerance holes in the manufacturing process.

The PCB industry on the other hand must provide precise indexing of all of the layers/laminations of the circuit board. It is common practice of the industry to pre-drill or machine these indexing features into each lamination and then manufacturing pins are used to align every layer controlling the relative position of each to exceptionally high tolerances. The current locating scheme utilized by the metal fabrication industry is shown in Figure 4.

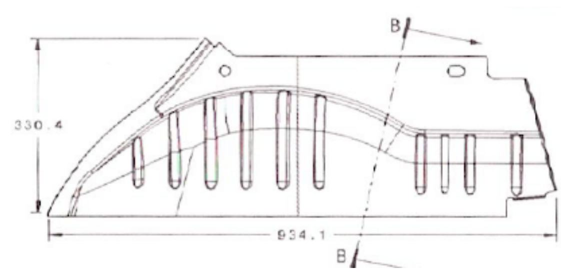

Figure 4, Typical 4-way and 2-way Datum & Locating Features utilized.

These Datum features will be cut (or pierced) in the forming/shaping operations immediately prior to the final compression molding process.

Post molding tooling requirements

When press molding CF/E pre-impregnated materials the components will be ejected (removed) from the mold in a hot condition. Remember that the polymeric ultimate cure, i.e. maximum glass transition temperature (Tg) has not been obtained. The epoxy polymer when hot will be quite soft and flexible. The molded component must be placed into a formed/contoured-cooling fixture. This soft condition is normally referred to as "Green". The green composite part will very rapidly solidify as the resin temperature falls below the critical "melt-temperature" of the polymer. The thermosetting epoxy resin will continue to react and perform as though a thermoplastic polymer until it has been post-cured/thermally processed and achieves the maximum Tg for it's specific resin chemistry. The compression molding process brings the molecular weight of the epoxy up to what is high enough for the component to be dimensionally stable.

The post processing heat treatment requirement is no different than that currently employed by the automotive industry when Advanced High Strength Steels are used.[3] Once the hot part has cooled sufficiently it can be racked and stacked in a normal fashion until presented in the body shop for assembly.

Pre-molding, forming, blanking, piercing and cutting operations

All of these operations will be considered to be exceptionally similar to current thermoforming processes used today with thermoplastic composites and sheet metal forming practices. I have seen major composites manufacturing operations utilizing press brakes and roll forming die lines. I have observed on-line demonstrations of forming thermoplastic composites by companies such as Fiber Forge Corporation[4]

High volume metal fabrication operations have migrated to the use of Tailored Blanks. Tailored blanks provide for the utilization of multiple thicknesses, material types and for the composites molder fiber orientation and optimized ply darting schemes. A press molding grade of CF/E will be dry to the touch at room temperature and will be handled and treated exactly like a thermoplastic composite, except the melting temperature will be significantly lower than the high performance thermoplastic resin systems. The materials will be tailor cut into the many required shapes with darting and scarfing as required. Then they will be quickly laminated and tacked together creating the unconsolidated laminate stack ready for consolidation.

Each heating cycle will drive the state of cure of the epoxy and the resin melt viscosity higher. These forming tools will be cooled in-order to quickly solidify the resin, stopping cure and freezing the form of the composite progressively shaped blank/charge. These forming dies and shaping tools will not be subjected to significant pressures or forces and need not be high strength steel. It is important to remember the high tensile strength of the carbon fibers. During the forming and shaping processes these fibers will flow slightly, but they will not normally break or stretch. If the forming process attempts to elongate or stretch the carbon fiber, the mold will probably be damaged or worn away. Not only is the tensile strength of the carbon fibers very high, they are also extremely hard and quite abrasive.

Mechanical assists, followers and other forming techniques used in the metal forming process will be adapted and used when thermoforming the CF/E composite blanks. Experience has proven that when laminating these types of materials the operation benefits greatly when areas adjacent to the area to be formed are restrained or by wiping the material in the direction of desired travel while permitting the complex shapes to flow, relax and conform to the surface you desire the material to adhere to. The highly automated techniques used in sheet metal forming operations today will probably work very well when press forming CF/E composites. In this case, the material will be entering the forming dies & molds hot and fairly flexible. The formed shapes will be exiting the presses cooler and rigid.

At this time, I believe the final step of the forming operation will be the trimming, punching and piercing operation. This will be performed when the material is still very hot and soft. This condition will be the best form for utilization of a typical shear or die cutting operation. A robotic CNC cutting machine may also be employed, as the material will still be partially cured and soft. This operation will remove exterior tabs, blank links and will place the standard 4-way and 2-way Datum holes into the shaped and ready to compression mold blank.

Part Design

Designing of high performance composite components for structural applications, especially for moderate to high volume production requires referral to accepted design handbooks. I have consulted the Automotive Steel Design Handbook[5] and the DOD Composite Materials Handbook, Volume 3. Polymer Matrix Composites, Materials Usage, Design and Analysis.[6]

There are many forms of carbon fiber epoxy (CF/E) composite materials. This section of the paper will focus on the selection of press molding grade epoxy reinforced with unidirectional (UD) carbon fiber. The molding material will contain 35% epoxy resin by weight and 65% carbon fiber by weight. Volumetric fractions will calculate out to approximately 50% resin and 50% carbon fiber. The composites design engineer will use this form of carbon fiber because it is the easiest form producible using commercially available carbon fiber. The author is assuming that the new renewable carbon fiber produced from lignin will be capable of being manufactured in this form.

3. S. Smith, 2008, Influence of Paint Baking Cycle on the Mechanical Properties of AHSS Welded Structures in Automotive Assemblies, Tata Steel.
4. D. Cramer, 2008, Hybrid Thermoplastic Composites Ballistic Helmet Fabrication Study, Fiberforge Corporation.

5. American Iron and Steel American Iron and Steel Institute and Auto/Steel Partnership, (August 2002, Revision 6.1), Automotive Steel Design Manual
6. United States Department of Defense, (17 June, 2002), MIL-HDBK-17-3F, Composite Materials Handbook, Volume 3, Polymer Matrix Composites, Materials Usage, Design and Analysis.

CF/E Design Considerations
The Common Hat Section

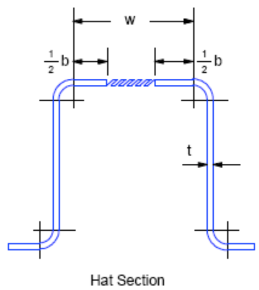

Figure 5

When a composites design engineer is presented with a common structural shape, reference the hat section shown in Figure 5, he/she must begin the process by first questioning or determining the primary loads and load paths on the product.

This is a very common structural shape used in many applications. The metal industry is more-or-less bound by the standard thicknesses of the metals being used. Tailor welded blanks could be utilized but not normally for the vertical walls, top of the hat section or the bottom return flanges.

The minimum material thickness for this shape using a 190 gm/m^2 CF/E-UD will be 0.030" (0.78mm). The inside and outside minimum radius which could be used will be that same 0.030"R. The design engineer would obviously prefer a greater radius and the preference is to utilize common radii whenever possible. The structural performance of the shape will be significantly affected by the size of the radii. Whenever possible I've preferred to specify a minimum radius of 0.0625 or 0.125", there are instances however when the minimum radius possible is required. The compression strength of the cross section can be significantly improved by designing with the 0.030 inside and outside radii. When issues such as a concern about "Bond-Line Read Through" are present then a larger radius at the outer panel to inner panel interface is preferred.

The 2005 Corvette Z05 CF/E-UD hood inner utilized a fairly significant bottom-of-the-hat flange radius of 6mm (0.25") and we molded the interfacing return flange at the minimum thickness of 0.030" with a fiber orientation of (0,90,90,0) creating an exceptionally soft/flexible return flange at the bond-line/interface with the hood outer. The vertical walls and top-of-the-hat section were bumped up to 6 plies of material and we placed 2-3 extra strips of single orientation zeroes along the top of the hat. Finally, when the bonding adhesive was applied to join Outer to Inner panel, we "cheated" the adhesive away from the inside radius of the flange at the bottom of the hat preventing any stiffening influence by reinforcing the unsupported web. The intent was to have the 6-ply CF/E-UD hood outer panel thicker and stiffer than the (effectively only 2 ply) return flange of the hood inner panel. Class-A surface finish was validated with no Bond-Line read. The structural integrity of the assembly conformed to all of the requirements, especially cross-car stiffness and crash/crush performance. It should be noted that the packaging under hood was designed for the use of SMC. Therefore the package space available under hood permitted us to utilize significantly deeper cross sections. The key mechanical and physical property differences Steel, Aluminum and CF/E-UD are compared to SMC in Table 1.

	Steel	Aluminum	CF/E	SMC	
Density	7.85	2.72	1.55	1.83	gm/cc
CTE (X 10^{-6})	7.3	12.5	3.6	7.3	in-in/^{o}F
Tensile Yield Stren.	38	19	51	11	Ksi
Tensile Modulus	30	10	8.5	1.5	Msi
Nominal Thickness	0.75	1	1.2	2.5	mm
Comparable Mass	589	272	186	458	gm

Aside from these differences between a CF/E-UD component when compared to an equivalent SMC component. The other materials/competitors Steel and Aluminum present more daunting design challenges. I have observed a major composite component manufacturer using a modified press brake to bend and form shapes very similar to the common hat section.

The process I spent quite a bit of time watching was similar to "Bending by Wiping" page 50, Wila, Press Brake Productivity Guide.[7]

> "With wiping, the sheet is also clamped after which the tool bends the protruding part of the sheet around the bend profile by moving up and down *(fig. 4.3)*. Wiping is faster than folding, but because the tool moves over the surface of the material, the risk of scratches and other damage is much greater, especially if sharp angles are involved. This technique is particularly popular for making panel-type products with small profiled edges. Using special tools, wiping can also be done on press brakes."

The primary differences I noted was the fact that the manufacturer was heating the area in the area of the bend radius and keeping the adjacent "flat" areas chilled/cool. After being formed the radius was chilled. The thickness of this U-shaped beam was rather significant at ~0.375" or greater.

On completion of the press brake forming operation, the shaped beam was placed into a normal autoclave mold, vacuum bagged and prepared for cure. The compression molding process utilizing the vacuum assisted flash type mold will require a few minor design

7. Wila Corporation (2008), Press Brake Productivity Guide, http://www.wila.nl/Wila-Press-Brake-Productivity-Guide-2007-2008.aspx?GB-1-79-60-58-0\

modifications to the hat section. The vertical walls of the hat are going to require some taper/draft. Knowing that the structures engineer (CAE finite element analysis) will be intolerant of anything less than a 100% vertical wall, the composites design engineer will negotiate for a preferred 3^{o} draft angle for each vertical leg of the hat. Removal of the part from the mold is normally difficult, but in the case of compression molding, the challenge may be less. Normally a cold/cool part will be extremely stiff, hard and will have razor sharp edges of resinous flash. The hot part will be somewhat soft, flexible and unfortunately fragile. I would propose to utilize a stripper plate or common ejection pins can be placed at/near/along the near vertical wall of the hat. The 4-way and 2-way datum's will have been punched or CNC cut into the flat area at the top of the hat. These will be utilized to rapidly locate/position the preformed tailored blank into the hot compression mold. After the hot part is ejected and removed from the hot mold, it will be placed into a form holding cooling fixture. It is possible to effect very minor dimensional changes in cooling fixtures of this type by applying controlled restraints. I have seen this effectively utilized to reduce and eliminate excessive spring back in reinforced epoxy moldings of similar shape and gauge.

The Multiple Stiffened Hat Section

The addition of reinforcing/stiffening elements placed along the top flat of the hat section, Figure 7, can be accomplished in one "hit" of a complex metal plug and die. The composites engineer when considering automation for high volume has to first consider how the experienced laminator/operator will accomplish/form these same shapes. The preplied tailored blank would require each dimple to be individually pressed into/onto the mold tool. The operator will progress from one dimple to the next permitting the material to fold into each.

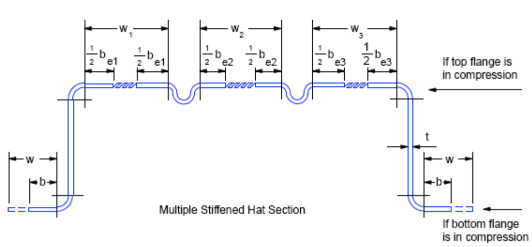

Figure 7 Complex Hat Section

A higher volume, nearly automatable process could utilize a modified Bottoming Bending operation, Figure 8, to progressively form each stiffening dimple.

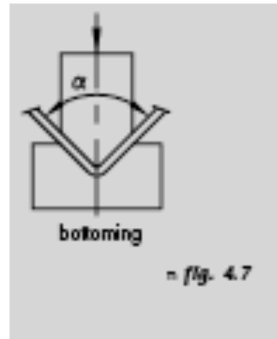

Figure 8 Bottom Forming

Spring boarding off of the folding operation discussed in the common hat section, I propose to heat the plug and cool the Die. The proposed forming process would then utilize a fairly common CNC press brake, the Accurpress America Advantage series for example.[8] This type of semi-automated forming press will provide guidance to the operator partially feeding the tailored blank into proper position for the strike/forming operation. The amount of inefficient hand labor should be minimized. It is very possible that this same press type could be used for the folding/wiping required for the vertical wall and bottom return flanges of this hat section.

Please understand that this engineer is speculating about the ability to utilize the press brake with bottoming tooling for shaping the dimples in the top of the hat. I know that in the hand lamination process the operator will be using a hot air gun to soften the material and a Teflon or Polypropylene wedge to progressively force/press the tailored blank into the mold. The Bottom Forming press brake operation using heated plug and chilled die is an obvious choice to experiment with for achieving significantly higher volumes of product.

The tailored and formed blank will then be set into the vacuum assisted flash type mold. Additional knockout pins will probably be required along the bottom surface of the dimples in the top of the hat section to aid ejection from the hot mold.

The requirement for the dimples themselves should be carefully discussed with the structures engineer. The composite design engineer would negotiate for the placement of strips of zero-degree CF/E-UD in the material lamination. The additional mass of these highly oriented strips may be an acceptable compromise and could impart the equivalent rigidity. There is a lot to be said for utilizing shape and geometry though. One or two thin strips of zero degree material can calm the propensity for flutter and oil canning. Structure-born noise is commonly resolved by adding mass to a metallic structure. The composites design engineer should negotiate need and determine the reason for the structures engineer requiring the dimples.

8. Accurpress America, (2011), Braking New Ground, www.accurpress.com

Closed Sections at High Volume

The author once spent a considerable amount of time investigating the feasibility of developing and producing these closed sections for a T-820 (Tahoe) and a Corvette Z06 Spaceframe Chassis, shown in Figure 9. General Motors Advanced Technology Vehicle once led an intensive program called the "Fuel Economy Learning Vehicle Program – (FELVP). The team formed was comprised of significant leaders in the aerospace composites industry accompanied by key engineering members of Delphi Chassis, famous (in the composites industry) for their development and high volume production of the fiberglass reinforced epoxy

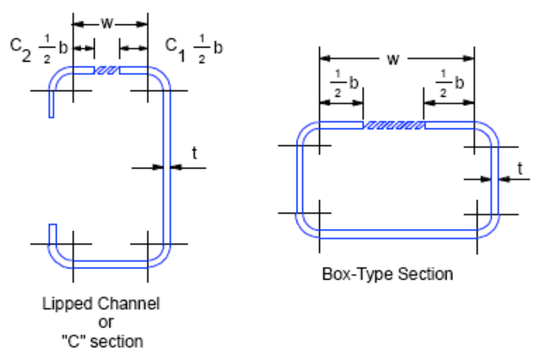

Figure 9 Closed Sections for Stiffening

unidirectional (GF/E-UD) Liteflex composite springs. This effort was not insignificant and our final conclusion was that both structures, the truck chassis and Corvette space frame could feasibly be produced at equivalent volumes and at a cost considered to be justifiable based upon the significance of the mass reduction and that effect on fuel economy. Unfortunately, neither project made it to the next step of the 5-step/gate R&D common product development process.

The manufacturing process we proposed was the same one we proposed, validated and delivered to the GM-ATV PNGV vehicle engineering team for the Precepts' (100 mpg PNGV demonstration vehicle) bumper beams, crash-boxes, door crash-beams and cross-car beams were produced and installed. The vehicle engineering team required a creditable and cost justified business case for the utilization of all exotic materials prior to permitting the product to be placed onto the vehicle platform. The same design approach and manufacturing technology was utilized for the frame/chassis of the body-on-frame Triax Concept Vehicle.

We started by preparing very large tailored blanks and then presented these to exceptionally large tube rolling machine. Note these machines are commonly utilized for rolling tailored blanks of golf club shafts, sail boat masts and other similar tubular elements. In our manufacturing model we proposed to extract the uncured/partially cured rolled tubular blank, then we proposed to form/bend this large diameter tubing utilizing heat and common tube forming equipment currently being used by Delphi Chassis for shaping the steel and aluminum blanks for the production Corvette base-car and Z06.

Our final manufacturing process was to utilize a relatively conventional tubular hydroforming press. In our manufacturing model we intended to utilize hot oil, warm oil and cold oil fluids similar to that used in the Quickstep method.[9] We intended to employ significantly higher fluid pressures than Quickstep currently utilizes. We felt that we could prove the modified (hot, warm and cold oil) process utilizing the same hydroforming dies and possibly even the same hydroforming press used to produce the steel and aluminum tubular frame rails for the Corvette sports car. The Chief Engineer and the Performance Car Team decided to pass on the project given concerns about cost and risk. Again, Body Structures and Chassis Engineering are exceptionally conservative (and metal mindset dominated) organizations.

Simple Structural Shapes

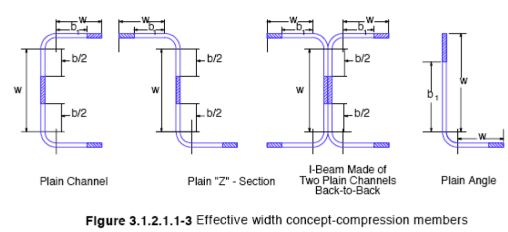

Figure 10, Simple Structure Shapes

Forming and molding the simple structural shapes shown in Figure 10, will be significantly simpler to produce than the more complex shapes discussed previously. I believe the tailored blanks will be dropped directly into the compression mold relying on the 4-way and 2-way datum holes to provide accurate and rapid indexing of the shape. Ejection of the hot molded parts may not even require anything more than a blast of compressed air. I imagine there will be a need for a simple formed cooling fixture.

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9. Quickstep Technologies Pty Ltd, (2011), Quickstep, The Out-of-Autoclave process for high performance autoclave grade materials. www.quickstep.com.au

Joining CF/E-UD

The back to back joining of simple structural shapes can be accomplished several ways. The simplest way may be to adhesively bond the components utilizing the rapid curing structural adhesive commonly used in the metal body shop, shown in Figures 11, 12 and 13.[10]

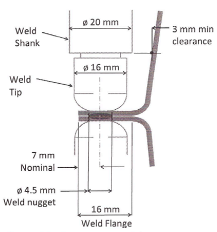

Figure 13.34: *Resistance spot weld flange requirements*

Figure 11 –Conventional Spot Welding

The concept of Melding, where the lamination of partially cured (in the area to be joined) then enabling these sections to be integrated into more complex structures without the fasteners or secondary bonding. This design/product development engineer would like to investigate the possibility of spot weld-bonding (possibly utilizing E-Beam technology) or other exceptionally fast heating and cooling means.

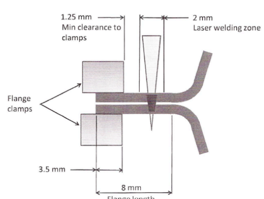

Figure 13.39: *Weld flange requirements for laser welding*

Figure 12, Laser Welding

The GM-ATV EV_1 electric vehicle body structure utilized a weld-bonded aluminum structure. Tata Steel has published a very interesting presentation about the structural performance of adhesives and weld bonded joints in metallic automotive body structures.[11] The summary of this report is:

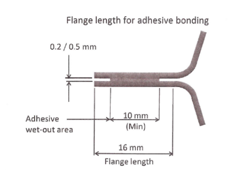

Figure 13.47: *Joint and flange required for adhesive bonding*

Figure 13 – Adhesive

- Microstructure, the adhesive does not negatively influence spot welds in AHSS
- Microstructure, No extra porosity/inclusions, weld hardness does not change
- Tensile Shear – TSS, Weld bonding has the highest strength and energy absorption
- Peel, Adhesive has the highest strength and weld bonding has the highest energy absorption.
- Cross Tension – CTS, Weld bonding has the highest strength and energy absorption, bonded only is weak.
- Crash, Weld bonding increases mean crash force considerably compared to spot welding.

The conclusions provided in this report are:

1. Weld bonding produces the best joint properties across all loading modes.
2. Weld bonding improves the mechanical properties of AHSS joints.
3. As material strength increases, joint strength increases
4. As material strength increases, energy absorption by the joint decreases
5. Weld bonding significantly improves crash performance
6. For optimized component strength weld bonding is recommended
7. Results indicate that in peel loaded weld bonded structures a reduced number of spot welds mays compromise joint properties

The EV1 body structure was an aluminum intensive weld bonded assembly. The spot welds provided adequate structural performance for transportation in the body assembly operation. Once the structure was passed through the tunnel oven curing the structural adhesive, sealants, blackout paint and primers the weld-bonded joints were exceptionally durable.

This composites engineer has spent a considerable amount of time in an aerospace assembly plant observing semi-automated solid riveting operations. I have also spent a considerable amount of time in the robotic welding area of a high volume automotive body shop producing 135 body structures per hour.

A typical riveted important aerospace structure requires an edge distance of 2 times the diameter of the rivet.[12] The rivet I am the most familiar with is a standard universal head solid titanium rivet (1/8" ~ 3mm diameter) per NAS-20470T4. Rivet-bonding using solid titanium rivets to tack the structure together is an interesting concept to discuss. When we utilize a 3mm diameter universal head solid rivet our projected required flange length will be closest to Figure 12 and the lower weight laser welded return flange.

One of the many potential advantages of a rivet bonding joining and assembly process will be the significant reduction in fixture investment. Assuming the manufacturing operation will CNC machine, laser drill or punch the many rivet holes into the return flanges prior to the joining operation. Not much dissimilar to how the

10. World Auto Steel, (2011), Future Steel Vehicle, Final Engineering Report, Pg 487, Section 13.2.1.9 Structural Adhesive.
11. Vrenken, J. (April 13, 2011), Structural performance of adhesive and weld bonded joints in AHSS, Tata Steel.

12. McDonnell Douglas Corporation (January, 1986), MCAIR Design Handbook, McDonnell Aircraft Corporation

printed circuit board manufacturing process indexes their many layers of copper clad laminate.

I once spoke with a senior Sikorsky composites manufacturing engineer while standing on the scaffolding of the Comanche CF/E primary structure assembly station. He told me some exceptionally interesting facts about their (Sikorsky Aircraft) findings about dimensional consistency and their discovery about needing fewer and simpler restraining and holding fixtures for their thin-wall composite structural components. The investment in handling and holding fixtures in a highly automated automotive body structure assembly plant is significant. The possibility for minimal fixtures and semi-automated solid riveting may provide acceptable risk reduction for the body structure assembly manufacturing management team permitting design engineering to move forward with prototyping and production feasibility studies. In my opinion, the E-Beam spot weld-bonding of partially cured CF/E-UD (near-Melding) process provides the highest potential for significant cost savings and maximum automotive body structure automation productivity.

Conclusion

This paper provides the composites design engineer with directional design detail for part, mold and assembly of high volumes of cost effective automotive composite components for body structure and chassis systems.

This paper has touched on a great many design topics and in my opinion; this author has left a great many important facts and details on the editing floor around his desk. The Steel and Aluminum Design reference documents used a significant documents. The amount of similar reference material found about compression molding of epoxy-impregnated materials was non-existent.

Additional Concluding Comments

One final set of concluding comments concerns the recently released Funding Opportunity Announcement by the United States Department of Energy titled "Innovative Manufacturing Initiative".[13] There are several paragraphs that I would like to place in this technical paper for the readers, engineers and managers examining this document to consider:

There is an important need for the "development of transformational manufacturing processes and materials technologies to advance the clean energy economy by increasing industrial and manufacturing energy efficiency, deliver the breakthroughs that the Nation needs to significantly reduce energy and carbon intensity throughout the economy over the coming decades, and revitalize existing manufacturing industries and support the development of new products in emerging industries."

There is an important need for "New manufacturing technologies and materials (which) can help reinvigorate existing manufacturing industries while supporting the growth and development of clean energy technologies and new industries in the United States. These advances typically involve high-risk, high-return R&D such as entirely new processing routes that require much less energy than current processes."

"It is essential that U.S. industry be prepared to meet its manufacturing challenges by advancing solutions to achieve significant reduction in energy consumption while also creating value and enhancing competitiveness. This will require a dedication to innovation and the development of transformational manufacturing processes, technologies and materials to create the next generation of U.S. industrial success."

Global Warming due to steadily increasing usage of hydrocarbons and release of huge quantities of carbon dioxide (CO^2) over the past several hundred years has created a need for us all to consider collaboration and sharing of ideas. We now understand how easy it has become for us to over fish our oceans, pollute our environment and how difficult it is becoming to provide safe haven and nourishment for the humanity of this planet of ours. Carbon Fiber Epoxy (CF/E) composites can and will eventually provide one of the solutions for the Global Warming threat. But, before this objective can be realistically be expected to be achieved, composites design engineers must share our knowledge, thoughts and ideas relative to how to make ultra-light vehicles using CF/E in high volume, cost effectively.

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