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COMPOSITE TRANSMISSION CASING FOR VOLUME PRODUCTION

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ABSTRACT

Weight reduction is always a key focus in driveline design. Drive System Design have been researching a step change in the design of casings for transmissions and drivetrain systems. This method explores the opportunities presented by advances in materials and manufacturing processed for significant reductions in component weight.

This research challenges aluminium and iron as the industry standard materials and casting as the manufacturing method for casings. Lightweight materials have been pioneered primarily in the motorsport industry but these are prohibitive on cost when considered in volume production. Either the material cost is too high or the manufacturing technique is too labour intensive.

The study identifies the potential that still exists in current design and manufacturing philosophy and explores some of the key challenges presented by new technologies including fabrication, composite construction, injection moulding and forging. It also sets out to solve some of the design issues created by the need for strength, durability, lubrication, cooling and NVH.

Ultimately, this investigation yields a design proposal for an aggressively light weighted transmission casing. It also presents evidence for potential component and tooling costs.

INTRODUCTION

With vehicle emissions targets becoming increasingly demanding, there is an urgent requirement to reduce vehicle weight. This is also relevant for the rapidly growing electric vehicle (hybrids included) sector, where the need to relinquish existing vehicle weight to the battery cells to achieve a satisfactory performance and range target is very real.

One area that has often been overlooked for large scale weight reduction is transmission and drivetrain component casings. When considering different materials for a transmission casing, we need to consider what the functions of the casings are. Primary functions to be considered can be identified as follows:

- Resist internal loads created by transmission of torque from input shaft to output shaft(s)
- Transmit beam loads resulting from powertrain mounting requirements
- Contain lubricating fluid
- Transfer internally generated heat out through casing. This could have an impact on the longevity of the casing material, therefore with anticipated vehicle life being a minimum of 10 years, material ageing must be considered.

Whilst a great deal of effort has been afforded to process refinement and component design optimisation, the most common base manufacturing process is casting, with aluminium alloys, magnesium alloys and cast irons being among the most commonly used materials. Figure 1 indicates mechanical properties for some of the more traditional materials used for this type of component. It will be useful to refer back to these values, as we investigate the advantages available from the new materials to us, are discussed.

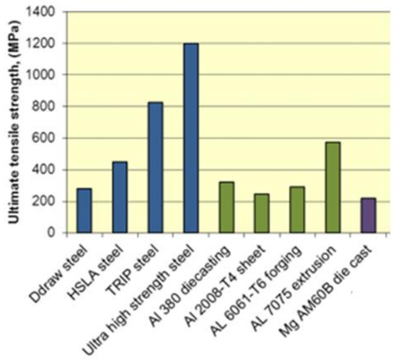

Figure 1: Mechanical properties for commonly used casing materials.

Significant progress has been made in recent years in the development of new structural materials. These materials, which include advanced ceramics, polymers, metals and hybrid materials derived from these, called composites, open up new opportunities for the incorporation of these technologies into transmission casing designs.

It is envisaged that in the coming years, new structural materials, as well as development of those that already exist, will provide a powerful leverage point for the manufacturing sector. Not only can composite components deliver superior performance over the more traditional materials, but they can also enhance the products into which they are used.

New structural materials can be classified as ceramics, polymers or metals as shown in figure 2-1. Two or more of these materials can be combined together to form a composite that has properties superior to those of its constituents. Composites generally consist of fibrous or particulate reinforcements held together by a common matrix as illustrated in figure 2-2. Continuous fibre reinforcement enhances the structural properties of the composite far more than particles do. However, fibre reinforced composites are also more expensive and difficult to produce into a component as complex as a transmission housing.

Composites can be classified according to their matrix phase. There are ceramic matrix composites (CMC's), Polymer Matrix Composites (PMC's) and Metal Matrix Composites (MMC's).

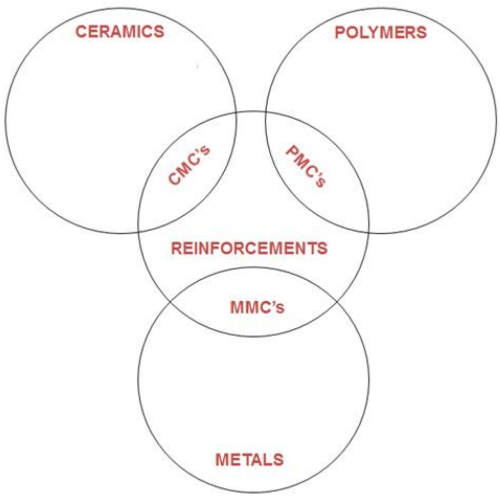

Figure 2-1: The Family of Structural Materials [1]

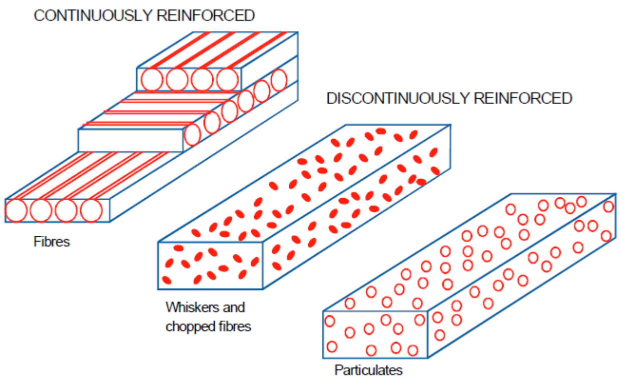

Figure 2-2: Composite reinforcement Types [1]

PMC's

The use of PMC materials in automotive applications has gradually evolved over the past two decades. With new materials and processing techniques being continuously developed for the plastics and automotive industries, there is potential for a more rapid expansion of these types of application in the future. PMC applications, both for small components and for more complex casings, could be a potential major growth area. This could have a significant impact in the automotive and associated supply industries if the required developments result in cost-effective manufacturing processes for these larger types of components.

Many plastics manufacturers are carrying out extensive research and development efforts with the aim of realising the potential benefits of PMC structures for the automotive industry. These potential benefits include weight reduction, which may be translated into improved fuel economy and performance, improved overall vehicle quality and consistency in manufacturing, part consolidation resulting in lower vehicle and manufacturing costs, improved ride performance (reduced noise, vibration, and harshness) and lower investment costs for plants, facilities, and tooling although this is dependent on cost/volume relationships.

However, there are still areas where major uncertainties still exist that will require extensive research and development prior to resolution. Examples of these are high speed, high-quality manufacturing processes with acceptable economics, satisfaction of all functional requirements, particularly crash integrity and long-term durability, plus the ability to repair and recycle.

A first consideration in the journey to reduce the weight of a transmission casing is obviously to consider a lighter base material. However, the immediate issue faced is whether a lighter material is available that retains (or improves) the mechanical properties required for the application. To maintain the cycle times required to produce casings in volume, injection moulding techniques (similar to high pressure die casting) could be considered. This leads to the use of reinforced plastics (such as polyamides with carbon and/or glass fibre reinforcement) or to high property plastics (such as special Peek plastics).

A typical material used in in this way is Polytron A50B02. This is a 50% Long Glass Fibre Reinforced Black Nylon 6.6 Heat Stabilized, UV Stabilized and suitable for an Injection Moulded application. Properties for this material can be seen in figure 3.

PHYSICAL PROPERTIES	**UNIT**	**TEST METHOD**	**VALUES**
DENSITY	g/cm^3	ISO-1183	1.58
WATER ABSORPTION (SATURATION)			3.4
MOISTURE ABSORPTION 23° C, 50% RH (SATURATION)			1
MOULD SHRINKAGE			0.1-0.3
MECHANICAL PROPERTIES	**UNIT**	**TEST METHOD**	**VALUES**
TENSILE YIELD STRENGTH	MPa	ISO-527	230
TENSILE MODULUS	MPa	ISO-527	18000
STRAIN @ BREAK	%	ISO-527	1.5
FLEXURAL STRENGTH	MPa	ISO-178	380
FLEXURAL MODULUS	MPa	ISO-178	16500
NOTCHED IZOD IMPACT STRENGTH +23°C	Kj/m^2	ISO-180	25
NOTCHED CHARPY IMPACT STRENGTH +23°C			28
UN NOTCHED CHARPY IMPACT STRENGTH +23°C			100
THERMAL PROPERTIES	**UNIT**	**TEST METHOD**	**VALUES**
HDT AT LOAD 1.8 Mpa	C	ISO-75	253
UL FLAMMABILITY		3mm	H.B.

Figure 3: Polytron A50B02 Mechanical Properties [1]

It can be seen that the density of this Polyamide (PA) is approximately 40% less than that of aluminium with comparable yield strength so the opportunities for component weight reduction are clear. However, there is currently a cost penalty for this material of almost double that per kilo to aluminium. However, if consideration is given to the reduction in component weight as a result of the lower density, it can be seen that the cost may not be as prohibitive as first thought. Add to this the energy savings that can be realised by a more efficient moulding process and the fact that the mould tooling will last considerably longer (typical die life for HP Die cast aluminium is ~100,000 parts as opposed to ~1 million parts from an injection mould tool) then this alternative looks even more feasible.

With the mechanical properties looking favourable at room temperature, consideration then has to be given to the material performance when exposed to the normal operating temperatures. These temperatures can be a sustained 120°C (248°F) with excursions up to as high as 150℃ (300°F). Figure 4 provides a modulus vs. temperature and moisture plot for a well-known and commonly used polymer, nylon 6. This material is shown in an unreinforced condition. As Nylon 6 is a semi-crystalline polymer, the results shown represent typical behaviour for this class of material. It can be seen that, as expected, the strength of the material reduces as the temperature rises. However, this performance reduction can be countered with the introduction of reinforcing constituents

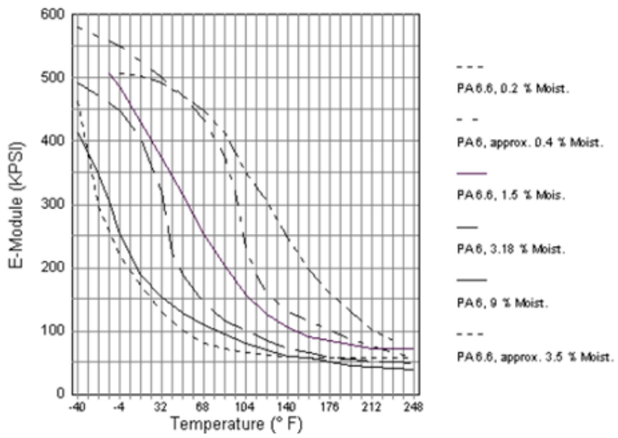

Figure 4: Effect of Temperature & Moisture Content on E-Modulus of PA 6 & 6.6 (www.intechpower.com)

A distinction is made between the two types of PA available. These are polyamides made of one basic material (e.g. PA 6) and polyamides which are made of 2 basic materials (e.g. PA 66). Polyamides have very good mechanical properties, are particularly tough and have excellent sliding and wear characteristics. Properties vary from the hard and tough PA 66 to the soft and flexible PA 12. Depending on the type, polyamides absorb different amounts of moisture, which also affect the mechanical characteristics as well as the dimensional accuracy. When thinking of the requirements of a transmission casing, resistance to impact has to be a consideration. Whether this impact occurs during operation or during an assembly or service environment, resilience to damage should be considered. Components already exist in transmission applications that are exposed to this type of use as can be seen in figure 5. It is therefore believed that this should not be a limitation for this type of material.

Another important consideration when choosing a polymer based material for this type of application is its compatibility with any fluids that it will come into contact with. Lubricant technology in transmissions is a constantly evolving area as the requirements of the lubricant are stretched further. This is a topic that can't be covered in this paper, but as can be seen in figure 5, polymer materials are currently being used in transmission applications where they are exposed to these types of fluids. It is therefore felt that this is not a restrictive factor.

Figure 5: Polymer sump for ZF6HP26 transmission

The base material chosen for a transmission casing, should be capable of retaining the desired properties at the required operating temperature, but also have the ability to reject that heat to prevent the temperature from continually rising. Many modern transmission systems (such as dual clutch and automatic transmissions) include heat exchangers to control the nominal operating temperature. In applications where this is not the case, as polyamides are not efficient thermal conductors, consideration should be given to the incorporation of heat transferring inserts into the mould in optimal positions.

Injection moulding these types of material will give consistent, high quality components but to achieve some of the features required in a transmission casing without post machining could be very difficult. Of course, small inserts can be included in the mould (or fitted after moulding with ultrasonic welding techniques) to accommodate threaded features for example, but accuracies required to accommodate components such as bearings could be difficult to achieve. It should also be noted that new materials and manufacturing methods are likely to introduce new failure modes which are difficult to predict in advance.

To overcome this, it is possible to include larger metal inserts into the mould and then inject the polymer around them make a hybrid structure. Conventional plastics are simply not strong enough to withstand the stresses exhibited within certain areas of a transmission casing. This issue could be overcome by using a metallic (aluminium or steel) skeleton to achieve the required strength in those specific areas and then over moulding with plastic to complete to shape required. This solution could be significantly lighter than the original component and also cheaper to produce.

In order to achieve these gains, the design of the component will be critical, especially the metallic skeleton, to achieve the performance requirements of the component whilst also achieving the maximum weight reduction. This is not considered to be restrictive however, as there are analysis tools available to achieve this. Couple this with the knowledge of the base materials and moulding techniques proposed and this approach becomes more feasible.

This solution also has benefits when taking into account end of life recycling. At present, recycling reinforced plastics (specifically if the directional fibres are continuous) is limited because separating the reinforced fibres from the base material is very difficult. Using a non-reinforced polymer means that this can be melted away from the skeleton component as its melting temperature will be much lower, and the skeleton parts can then be recycled using conventional methods.

Another manufacturing method to consider is that of using traditional carbon fibre sheets. Because of the very high mechanical properties of these materials, the resulting casings can be lighter and stronger than those made using other methods. These materials and processes are well known in the aeronautics and motorsport industries, but at present, the materials are very expensive. Replacing the carbon fibres with glass can reduce these costs, but the biggest restriction in using this technology in the automotive industry is the moulding process itself. Once the layers are deployed into the mould, the injection of special resins at high pressure can achieve 2 minutes cycle time. However, it is the deployment of the lamination layers that is currently the most labour intensive activity ultimately resulting in long cycle times. Research is ongoing in this area with improvements in automation and the use of robotics during the lamination process being sought. It is believed that in the near future, new robotic techniques and processes will be developed to achieve feasible cycle times. Nevertheless, the costs are likely to remain high and will make this method only suitable for low volume high performance cars.

It can be seen that the larger manufacturers are already beginning to realise the advantages of adopting these techniques into powertrain components. However, the risks and costs associated with taking components of this type straight into a production environment could be considered too great. It may be more viable for manufacturers of niche products to adopt these technologies where the cost implications may not be so restrictive. Once the successful adoption of these technologies is realised, they will almost certainly filter through to the mass market.

Also of worthy note is the fact that some plastics companies are beginning to indicate that nanotubes may also allow a fully injectable material with greatly enhanced properties although this appears to be very much at the research stage.

MMC's

Metal matrix composite materials have found application in many areas of daily life for quite some time. Materials like cast iron with graphite, or steel with high carbide content, as well as tungsten carbides, consisting of carbides and metallic binders, all belong to this group of composite materials. Substantial progress in the development of light metal matrix composites has been achieved in recent decades, so that they could be introduced into the most important applications.

In the automotive industry, MMCs have been used commercially in fibre reinforced pistons and aluminium crank cases with strengthened cylinder surfaces as well as particle-strengthened brake disks. These innovative materials open up unlimited possibilities for modern material science and development. The characteristics of MMCs can be designed into the material, custom-made, dependent on the application. This material group becomes interesting for use as constructional and functional materials, if the property profile of conventional materials either does not reach the increased standards of specific demands, or is the solution of the problem.

Metal matrix composites can be classified in various ways. One classification is the consideration of type and contribution of reinforcement components in particle, layer, fibre and penetration composite materials (see figure 6-1). Fibre composite materials can be further classified into continuous fibre composite materials (multi- and monofilament) and short fibres or, rather, whisker composite materials (see figure 6-2).

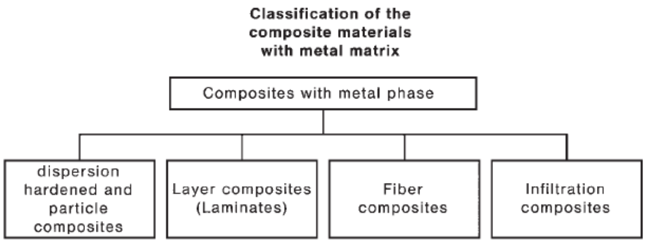

Figure 6-1: Classification of composite materials with metal matrixes [2]

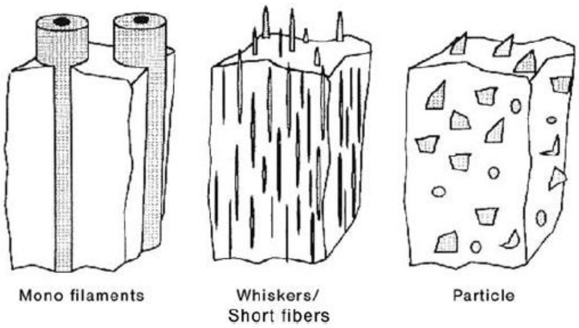

Figure 6-2: Schematic presentation of three shapes of metal matrix composite materials [2]

Composite Metal Technologies Ltd. (CMT) is an advanced materials technology group whose principal activity is the development and production of continuous fibre reinforced aluminium matrix composite (CFR-AMC) components, through the exploitation of its proprietary Advanced Liquid Pressure Forming (ALPF) manufacturing technology. This technology has potential in the incorporation into transmission casings to achieve the goal of a stronger, lighter component.

Woven fibre preforms can enhance the properties & reduce the costs of CFR-AMC materials. These materials incorporating 3D preforms are marketed as ‘Aluminium Fibacore’. These components offer significant weight and performance benefits over conventional unreinforced materials such as steel and other common alloys, as well as being able to tailor the mechanical properties achieved. They can also provide the strength and stiffness of steel with the weight and inertia similar to aluminium.

Al-Fibacore resembles plastic composites in structure, but utilises a metal rather than plastic matrix material & alumina rather than carbon or glass fibres. The Aluminium-based matrix materials are all recognisable as currently used alloys (AL 99.99, LM25, L99, 6061) and the fibre is continuous alumina fibre reinforcement (3M Nextel 610). This fibre is available as unidirectional, 2D or 3D woven fibre preforms and once formed into the matrix has a fibre volume fraction typically of up to 0.65 or 0.40 for 3D preforms, as can be seen in figure 7.

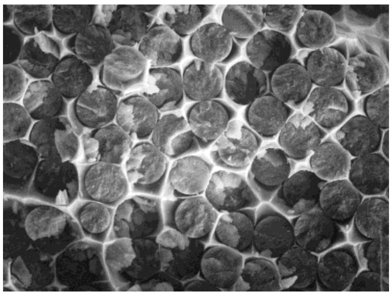

Figure 7: Fibre volume fraction of 0.65 [4]

When compared to conventional casing aluminium, the following mechanical properties gains can be achieved:

- Longitudinal stiffness 240GPa (up to 4x)
- Longitudinal tensile strength 1600MPa (up to 3x)
- Longitudinal compressive strength 1700MPa (up to 5x)
- Lower thermal expansion 7 ppm/ºC (30% of aluminium)

However:

- Reduced ductility and toughness (1% elongation)
- Higher density (+26%) (due to the added fibres)

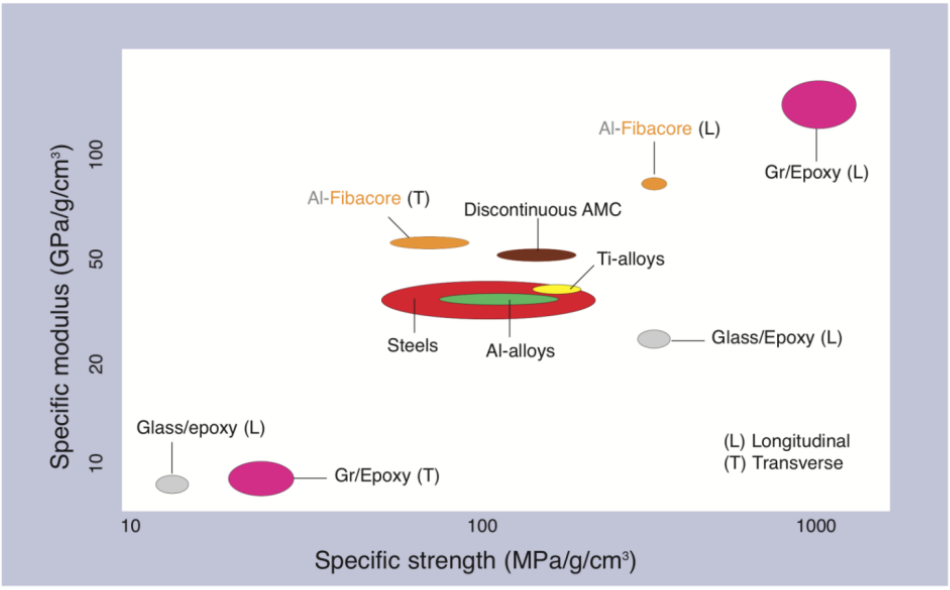

Figure 8: Strength advantages of AL Fibacore [4]

One of the advantages of this technology is that full or selective fibre reinforcement can be achieved. Therefore, even though the density of the material is higher than conventional aluminium, inserts can be selectively positioned into an aluminium casting to give strength “where it’s needed”. This results in a thin wall casing with strength in critical areas and an overall weight saving. It also means that the change in supply chain is minimised as the inserts can be designed into tooling that can be used in conventional casting methods. Also, the comparatively high cost of fibre can be offset by using Al-Fibacore more sparingly. The inserts can be fused to the overcast aluminium with no mechanical interlock required

An example of this can be seen in figure 9 (the preform being shown on the surface for clarity although it would actually be cast sub-surface).

Figure 9: Al Fibacore insert positioned on an aluminium casing. [4]

As this is a relatively new technology, the Alumina fibre manufacturing process (chemical solution deposition) results in high fibre costs. The current fibre supplier (3M) is collaborating in efforts to reduce costs through manufacturing process efficiencies. Currently the Unidirectional Al-Fibacore material cost is €108/kg. Reductions in fibre density facilitated by the use of 3D woven preforms, has reduced this to €73/kg. Alternative fibre grades awaiting test are up to 30% cheaper again with the latest '3D-UD' concept being €62/kg. At present, this method almost certainly will result in a component cost increase so a cost versus benefit study will be required at application level. However, CMT's target in the next 5 years is to achieve the current €/kg targets of automotive volume OEMs.

EMERGING TECHNOLOGY

DuPont are suppliers of high performance polymers and reinforced polymers and one product that they are currently developing is Vizilon®. Vizilon® TPC is a technology that combines strength and stiffness into a lightweight structure to help automakers replace metal and continue to reduce weight in structural vehicle applications. This material is produced in sheet form and offers better stiffness properties that can't be obtained with standard thermoplastic resins, creating more opportunities to reduce vehicle mass. Typical mechanical properties can be seen in figure 10.

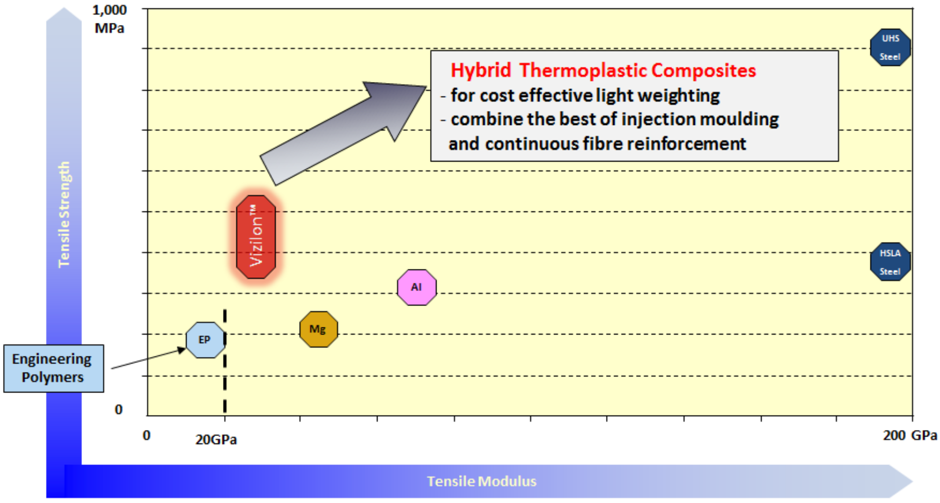

Figure 10: Mechanical property advantage of Vizilon® over traditional materials [3]

The product comprises of a base composite sheet that is formed into the basic shape of the component. This is a glass filled Polyamide sheet that is available in four types. All four sheets have two fibre directions, two sheet types are balanced (i.e. they have the same number of fibres in both directions whereas the other two sheet types are unbalanced and have 4 fibres in one direction for every one fibre in the other direction. Consideration needs to be made during the design stage as to the location and direction of the forces to best utilise this material to achieve optimum component strength.

DuPont are also considering the requirements of the manufacturers by incorporating into the material:-

- simple glass architectures for fast impregnation, strength and stiffness
- integrated stabilization technology to meet auto specifications
- easy processing during (pre-) forming of laminate

- good healing with over-moulding resin for wide processing window
- fully characterized for FEA modelling

The component manufacturing process is thus:-
(15 second cycle time):
- take the base sheet material and place into an infrared oven
- place into a heated tool and compress

Then
(45-60 second cycle time):
- Water jet trim component to final shape
- Insert into injection moulding machine for over mould.

Components can be fully or partially over moulded with ribs, bosses etc. and inserts can be included in the mould as required to complete the component. At present, for a transmission component, it would be necessary for the component to be over moulded on both sides as the base polymers used for the composite sheets are not oil resistant, but this is an area that is undergoing further research.

An example of a typical product can be seen in figure 11.

Figure 11: DuPont Beam Test Tool. [3]

One area of research has been in the interfacial layer between the base composite sheet and the over mould. The test results in figure 12 show that the interfacial layer remains intact with the crack propagating into the constituent material and not along the interface.

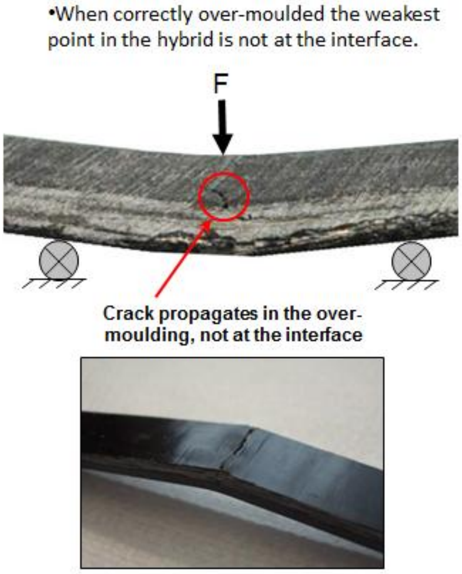

Figure 12: Interfacial Bond Strength [3]

With the advancement in materials technologies and the constant improvement in manufacturing techniques, the capability to produce light weight transmission casings already exists. The challenge remains to try to reduce the additional costs incurred over conventional methods.

The cost to benefit ratio needs to be assessed at application level but if the incremental increase in cost of reducing weight using this type of technology is lower than in other areas, the development of these processes for use in transmission casings will naturally follow.

CONCLUSION

If a manufacturer is seeking a component weight reduction whilst minimising the effect on the supply chain, then it would appear that the adoption of MMC's in some form is the best solution. By redesigning components to accommodate the preformed composite inserts where stresses are high, casing wall thicknesses can be reduced in those areas where stresses are low and the number of casing ribs required can also be minimised. This could result in an estimated overall component weight reduction in the order of 10-15%.

Alternatively, if the manufacturer is looking for maximum reduction in component weight, then the use of a polymer based material is considered to give the biggest gains. To assess which method is most appropriate, a component specific feasibility study would be required.

There exists a growing use of these materials for non-structural (or limited) applications. However, there still remains significant risk in adopting new technologies, but looking forward to the challenges of achieving emissions legislation will require a step change. Light weighting will be a key consideration and it is likely in the short term that we will see advances in local material property improvement of aluminium casings (either by process or material enhancement). The step to structural plastics will be a medium term development (~10 years) when learning from current applications and new failure modes is better understood. It is the author's opinion that the polymer based materials offer a real opportunity but require a very different approach to casing design to ensure the manufacturing process remains simple. One only has to look under the bonnet of a modern car to see how common the use of plastics is becoming including structural applications. There is a growing body of research for use of plastics within the transmission ("The use of plastics in automotive gears" [5]) but further work is required.

It is clear that initially these will incur a higher cost than traditional materials (i.e. aluminium) and that cost pressures have seen use of magnesium decrease. However, as mentioned, the emerging Premium Electric Vehicle segment has very real reasons for aggressive weight reduction of all components, hence the extensive use of carbon fibre on the new BMW i3. In terms of adoption, it is likely that this segment will drive the use of plastics and the inherent damping of these materials, may bring advantages in NVH which is another challenge for transmission within these vehicles.

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