Closed-cell foam seals (Courtesy of Butser Rubber)

Our flexible friends

Wayne Ward discusses the current and potential future applications of polymers and polymer-matrix composites in the race powertrain

The modern race powertrain has much in common with its forebears of the 1930s; in many cases, the engineers of that time would recognise everything we see now in an engine or transmission. They would undoubtedly be impressed with the extent to which constant evolution has brought the modern powertrain in almost every regard – from the wonderful engineering and manufacture of modern components to the extremely high engine speeds and output per unit of displacement.

In terms of materials though, engineers from almost any period in the past can hardly fail to be impressed. The levels of strength and durability of many materials continues to develop at great pace. The types of material would largely be familiar – crankshafts are still made from iron or steel, the main engine castings are still made of iron or aluminium (although the absence of magnesium might cause some puzzlement) and pistons are generally still made from aluminium, some grades of which are almost unchanged over a number of decades.

However, there are materials that are now commonplace in or on the modern race engine and powertrain which engineers from two or three decades ago would not recognise. These are the non-metallic materials.

There are two main groups of bulk non-metallic materials (as opposed to non-metallic coatings) used in race engines and transmission – polymers and polymer-matrix composites. Ceramics, while finding greater use, are found only in very limited applications.

The case for non-metallics

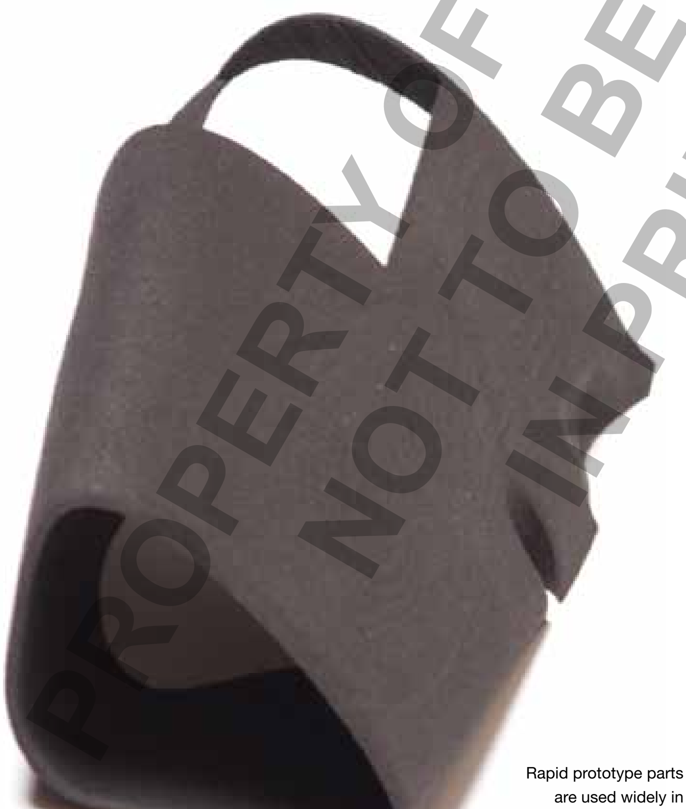
There are some applications where non-metallic materials are simply the only thing that will do the job in question at reasonable cost. A large number of seals used in a race powertrain come into this category. Having low stiffness, and capable of large amounts of elastic deformation (why do we continue to call them plastics?), polymers – of which rubbers are the most common for this type of component – are perfect for everything from crankshaft seals with high surface speeds to quasi-static O-rings.

There are other applications where material substitution for reasons of low density leads people to consider the use of polymers. Lightly stressed components typically made from aluminium can be replaced with polymers in many cases, providing that care is taken to select the correct material for the application, taking into account the service temperature and any chemicals (coolant, fuel, oil and so on) likely to come into contact with the parts.

Cost can also be a consideration. In many cases, moving from metallic to polymer components won't yield any cost savings, especially where parts are machined from solid. However, where production quantities are high enough, polymer and polymer-matrix composites can offer some very worthwhile cost savings, coupled with other benefits such as lower mass. In such cases, we have to consider manufacturing techniques such as injection moulding, vacuum forming or composite lay-up, which can be a little alien to race powertrain engineers.

In many cases, polymer or composite components would be difficult or impossible to make from conventional metallic materials. Airbox trays, air-horns (snorkels), other ducts and heat shields are good examples here.

Composite materials in particular provide components whose specific stiffness (measured by modulus per unit mass) cannot be rivalled by conventionally manufactured metallic materials. Carbon-fibre composite components consisting of two 'skins' separated by a honeycomb centre or other low-density core have exceptional bending stiffness for a given mass.



Rapid prototype parts are used widely in race engine development as materials and processing improve (Courtesy of RP Support)

Polymer, ceramic and composite components also offer low thermal and electrical conductivity compared to metallic parts, and in many instances, these properties are put to good use. Hybrid powertrains have been developed in racing for a number of years, and the arrival of the KERS initiative in Formula One, while being some ten years behind the first application of bespoke hybrids in racing, has given new impetus to the development of such technology. Hybrid systems use polymer composite materials for battery and power electronics casings, and make use of polymers in the power electronics themselves for electrical insulation. Materials with low thermal conductivity are attractive for a number of applications for race engines, particularly on the intake and exhausts. For inlet systems, mitigation of heat transfer to the incoming charge is important, and for exhausts, retention of heat within the exhaust flow can have a number of benefits.

The rules

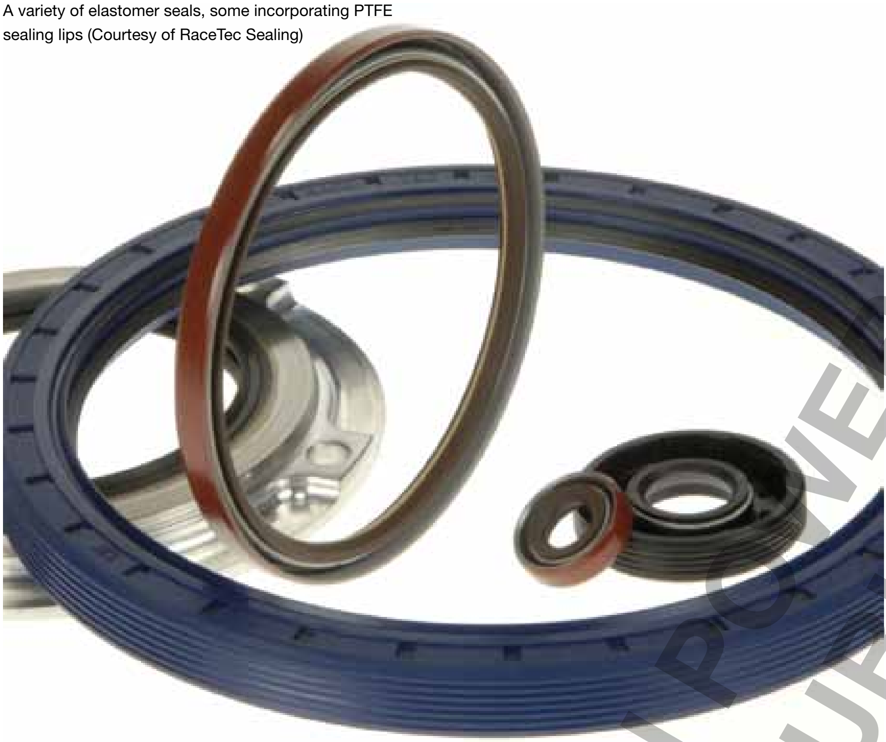
Like many of the rules controlling the use of materials in racing, those governing the use of polymers, ceramics and composites seem a little illogical. The rule-makers might argue that they are trying to create a level playing field and prevent excessive spending. However, we have seen that teams will inevitably choose to spend the money that they have available, and by channelling these resources into diminishing returns with conventional materials, racing is missing out on the chance to develop worthwhile new technologies.

Formula One is a good example of over-proscription in material regulation. While Formula One cannot use anything other than aluminium for crankcases or cylinder heads – and composites are banned even for local use in these components – we have the situation where composite cylinder blocks are being produced for sale, and these can be produced at reasonable cost, either to new designs, or for existing applications. These advanced technology 'demonstrators' show how such technologies can be applied at reasonable cost (more of this later). It is a strange situation where any new technology can be developed and used by 'lower' race formulae but may not be used in top-line racing.

The rest of this article will deal with the past, current and potential future applications of non-metallic materials in the race powertrain. There is one visionary engine that will be constantly referred to in this regard – not to refer to it would be to ignore 'the elephant in the room'. The 1984-85 Polimotor race engine (a 2.3 litre double-overhead cam four-cylinder unit) still represents the zenith in terms of the application of non-metallic materials in the internal combustion engine, and those taking up the baton since then have generally done so in only a very limited fashion.

Its goal was to answer one simple question: can major components in an internal combustion engine be successfully made using polymers? In addition to building and racing an engine featuring a large number of polymer and composite components, the project ▶

A variety of elastomer seals, some incorporating PTFE sealing lips (Courtesy of RaceTec Sealing)



examined the feasibility of using polymers for other types of engine, notably overhead valve (pushrod) engines. The paper by Gaudette (1) details the use of polymers and polymer-matrix composites in this extraordinary engine.

Cylinder blocks and sumps

The work originally pioneered in the Polimotor project was the use of a polymer-matrix composite cylinder block. Based on a matrix consisting of epoxy and phenolic polymers with graphite fibre reinforcement, the cylinder-block production technique has been refined in subsequent years using different matrix materials, and composite cylinder blocks are being produced currently, both for sale and as advanced technology demonstrators to show the possibilities of the production process.

As we might imagine, given the complex nature of such castings, the reinforcement is in the form of short fibres to allow the material to fill the mould cavities. The production process is intended to allow gravity filling of moulds rather than injection moulding. Whereas the general intention with metals is to produce an isotropic material with properties equal in all directions, it is seldom possible to do so in complex cast-metallic components. With large composite 'castings' it is very much the case that substantial and planned anisotropy is the norm, with strategically aligned and placed directional reinforcements selectively being used to improve strength and stiffness in important locations for structural components. Such modern equivalents of the Polimotor block still use the same basic materials in terms of matrix and reinforcement, but these have of course been developed during the intervening period.

Cam/rocker covers

Polymer cam or rocker covers are common in production engines, but still remain relatively rare in race engines. One obvious reason is that many of these items are structural in a race engine, feeding chassis loads through the engine to the engine mounts. Composites have been used for these components, probably most publicly by Cosworth, which used carbon cam covers on the Aprilia 990 cc MotoGP engine, and again on its 'beam head' Formula One engines. The beam head was a clever concept that allowed a very lightweight cylinder head during the days when there were no regulations governing minimum engine mass or centre-of-gravity position. The cams were inserted from the side of the head rather than the top, and the closing panels, which were non-structural, were made of a composite.

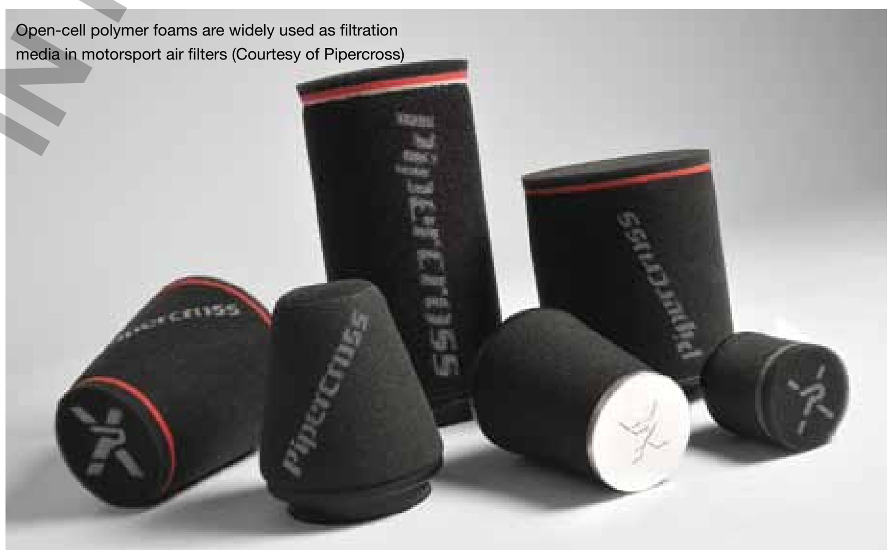
Pistons/pins/rings

Polymer materials have been considered and used for pistons. In terms of use as a bulk material, however, polymers are not well suited for use as a piston. They lack thermal conductivity, strength and stiffness, and so do not seem to be a good candidate for piston manufacture. The Polimotor engine took a pragmatic approach in the 1980s by combining a metallic piston crown and integrated pin boss with a Torlon poly-amide-imide (PAI) polymer skirt to good effect. Later designs used a greater proportion of polymer in a design that used the polymer as a more structural member. A particular feature of the piston was a high top-ring position in the metallic structural part of the crown, with the second and oil-control ring grooves in the polymer skirt.

The use of polymer coatings on pistons continues today, and has only relatively recently begun to be supplanted by DLC. These are generally with PTFE polymer particles suspended in a resin binder.

The use of polymer coatings is widespread in racing and is variously credited with helping the piston skirt to 'wear in' to the optimum profile. The study of piston skirt optimisation by Yagi and Yamagata (2)

Open-cell polymer foams are widely used as filtration media in motorsport air filters (Courtesy of Pipercross)



showed the value of using a polymeric skirt material in the development piston skirt geometry, although their method used a thick composite coating rather than a complete polymer skirt.

Polymer 'buttons' used to retain piston pins in place of circlips have found some success in racing, although the tendency toward larger bores and short, light piston pins means these components have not found widespread use, and are most suited to the older type of pistons (the so-called 'pot' pistons), which are essentially cylindrical to a point below the piston pin bore. Buttons pressed into the piston pin contact the cylinder bore and thus control pin-end float. They rely on having good tribological characteristics to prevent wear that would lead to excessive pin float. The piston pin of the Polimotor engine consisted of a thin metallic sleeve with a polymer core, and was retained with polymer buttons rather than traditional circlips.

In terms of piston rings, the top ring bears the brunt of combustion pressure loads and sees the highest operating temperatures. The Polimotor engine made use of polymers for the second and oil-control rings. They were protected to a large extent from high temperature by the fact that they were housed in the non-structural polymer skirt. The rings were said to exhibit good wear behaviour, although the oil ring was not used in the race engine.

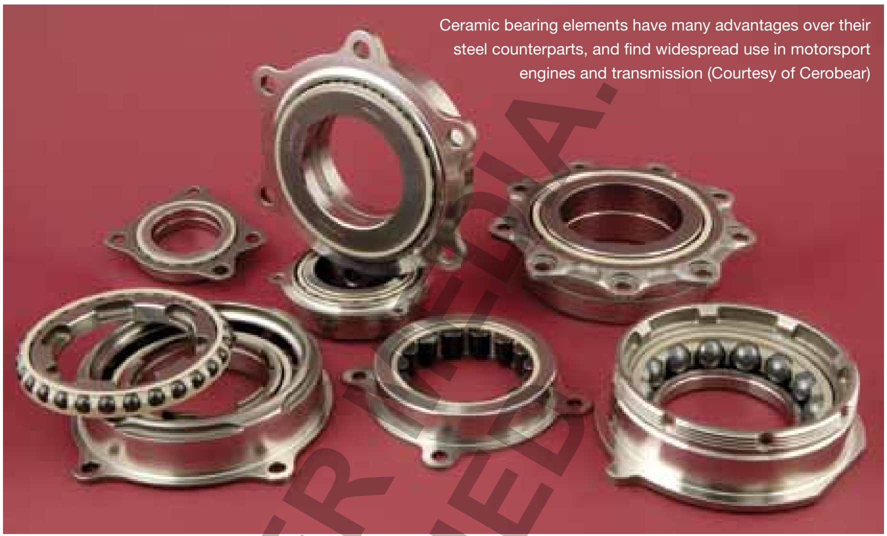
Valvetrains

The use of polymers in the valvetrain is already quite widespread, especially where pneumatic valve return systems (PVRS) are used, as is the case in Formula One and MotoGP. These use three polymeric seals for the maintaining pressure in the system. There is the main PVRS seal, which is generally a moving seal on the PVRS piston, although static seals have been used with success against a piston. The second seal acts to prevent leaks of pressure past the two halves of the valve collets, and the third is the common valve stem seal. The valve stem seal is commonly used on other race engines.

The advantages of low-mass valvetrains are well known and documented. The paper by Kanzaki et al (3) goes into some depth regarding the advantages for friction, engine size, engine mass and vehicle mass of low-mass valvetrain components. The Polimotor was again adventurous in this regard, with a polymeric valve stem being used with a metallic valve head, for inlet valves only. Given the high thermal demands of the exhaust valve, a conventional metal valve was used. For the inlet valve, a metallic valve head was attached to the polymer stem by the use of a screw thread, with a metallic insert in the valve stem containing the thread. This is unlikely ever to find widespread use, especially in racing, where valve stem stiffness is very important. However, the mass saving compared to the standard valve was 79%.

The Polimotor project examined various engines from 1.6 litre to 5 litre capacity; one part that was tried in all these engines was valve retainers. These offered a 41% mass saving compared to the standard steel retainer.

Polymer valve guides have been tried with varying success, and



Ceramic bearing elements have many advantages over their steel counterparts, and find widespread use in motorsport engines and transmission (Courtesy of Cerobear)

might one day become of limited use in racing, especially for the inlet valve guide. Exhaust valves rely more on thermal conduction through the valve guide to dissipate heat, and in sodium-cooled valves this means that guide temperatures are far too high for conventional polymers to be used.

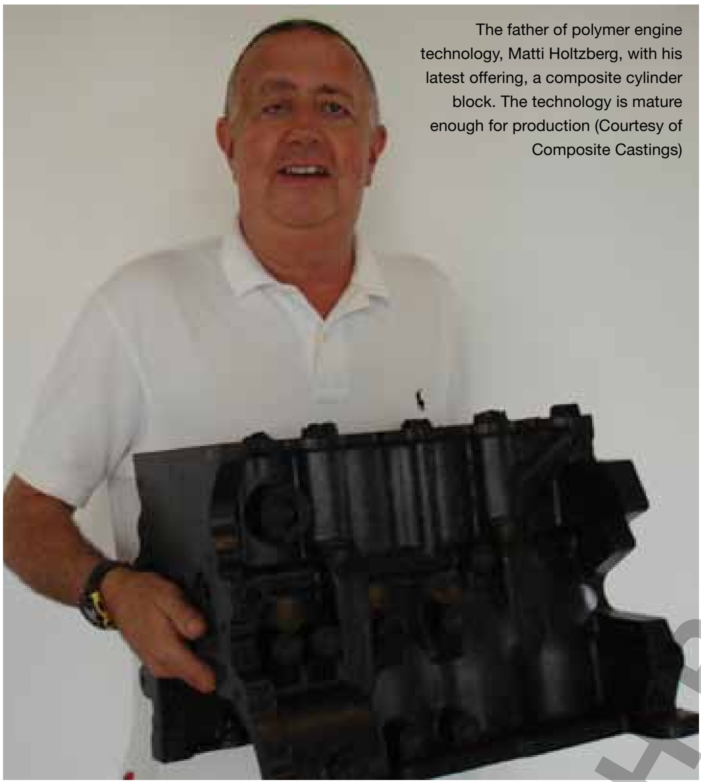
Ceramic valves are of interest for both race and production engines, and there have been limited trials of ceramic valves in race engines, although little evidence exists to suggest anything more than small-scale trials have taken place. Technical regulations in the main race series with the budget to develop such items mean they cannot be used. Ceramics offer low density and high stiffness. The specific modulus, which is the ratio of elastic modulus (a measure of material stiffness) to density is about 94 GPa/(g/cc) for silicon nitride (Si_3N_4) where a typical measure for metallic valves in materials such as steel and titanium is about 24 -28 GPa/(g/cc).

Polymer or composite flat-tappet cam followers for overhead cam engines using metallic inserts on the working surfaces would not be difficult to produce, and indeed were used in the Polimotor engine with success. Aluminium has been widely adopted as a cam follower material based broadly on the same design principles. We can also imagine that composite finger followers were investigated in Formula One when material regulations were less restrictive. If steel inserts could be reliably integrated, the stiffness and density of composites would make them attractive for use as cam followers.

The Polimotor project also examined components that were not used in their race engine; rockers and lifters as used in pushrod valvetrains were produced. The rockers incorporated metallic inserts in regions of high stress, such as the pivot, pushrod socket and roller shaft mount. The roller lifters as detailed in Gaudette's paper used polymers for weight reduction only, forming the wall of the lifter 'cylinder'. Versions in which the polymer was used as a structural member were planned to be tested after the publication of the paper.

Con rods

Can we conceive of a non-metallic con rod? The Polimotor engine used such an item, and strong anecdotal evidence exists that at least one Formula One team built and tested full engines equipped with polymer-matrix composites with carbon reinforcement in the form of long fibres. The application of composites to con rods is technically difficult, and would require the fibres to be long and to wrap around the little end of the con rod without discontinuity. Indeed, the use of such con rods might well be better suited to engines where no split in ▶



The father of polymer engine technology, Matti Holtzberg, with his latest offering, a composite cylinder block. The technology is mature enough for production (Courtesy of Composite Castings)

the con rod is required, as in those engines with built-up crankshafts.

Certainly it would not be an optimal application of composites for con rods if the components were to be machined from a billet of either short-fibre reinforced material or 'billet' material built from layers of 'pre-preg' material. Pre-preg is pre-impregnated un-cured composite material that can be laid into the required shape before curing under heat and pressure. However, this is exactly the method used in the Polimotor engine, and the con rods ran successfully at the time. The main disadvantage was said to be the cost of the parts. Load transfer to the fibres from metallic inserts would be of critical importance in any polymer-matrix composite con rod. The geometry and behaviour of the split-line would also require very careful study.

Pumps

Oil and water pumps are fairly benign environments for polymers, and polymer casings and internals could be used more widely than they are at present in racing. Non-metallic pump casings are used in some production engines, and polymer water pump impellers have been used for many years. The electric water pump, beloved of several low-budget race series, is an example of a 'plastic' pump being used in racing.

In pumps with non-contacting rotors, such as Roots-type oil pumps, polymer rotors can be used, and it is also common to apply polymer coatings to these rotors where metallic items are used in order to give the rotors a degree of 'embeddability' in order to 'absorb' small particles of foreign matter. Polymers also find applications in pumps for other components such as pressure-relief valve pistons, valve seats and so on. These are typically high-temperature polymers that are less likely to suffer serious loss of mechanical properties at operating temperatures.

Pumps will generally require the use of an efficient seal around the input shaft, and these are often based on elastomers. A recent trend in lip seal design has been to incorporate a PTFE sealing element with an otherwise standard-looking elastomer (rubber) seal. These offer greater scope for doing clever things such as machined helical features on the sealing lips.

Water pump seals in particular may also incorporate ceramic sealing elements. In these 'mechanical' seals, the sealing is done by the opposing faces of ceramic sealing rings which are produced to extremely tight flatness tolerances. These two rings are forced together using a helical spring that forms an integral part of the seal.

Gears and pulleys

Plastic pulleys have been commonly available in filled polymers for many years and were a feature of the Polimotor engine for both alternator drive and cam timing drives. Plastic gears are commonly used in pump drives for automotive applications, and these offer a degree of compliance that metallic gears do not have.

Ducts and pipes

External ducts and pipes for routing oil, air and coolant are ideal applications for non-metallic materials. Composite pipes with long-fibre carbon reinforcement in a polymer matrix are commonly used for both water and oil transfer in race applications, and offer reliable low-mass components. Where there is little pressure differential between the fluid on the inside of the duct and the pressure on the outside, long-fibre composites are not required, and this opens the way to more conventional production techniques such as injection moulding and vacuum casting.

Rapid prototyping techniques are often used for air ducting, and might prove to be reliable enough for production of water or oil ducts. I tried using rapid prototyping for a prototype water pipe about a decade ago but without success, although the reasons for failure appeared to be concerned with the limitations of the particular manufacturing equipment being used.

Inlet systems

If we take the example of a modern single-seat racecar, there is little that isn't made of – or hasn't at some point been made of – non-metallics, from the inlet above the driver's head to some way into the cylinder head. The case for non-metallics here is strong, and the working environment lends itself to the use of polymers and polymer-matrix composites. The temperature is low enough such that many polymers are perfectly suited to the service conditions. For large, lightweight pieces requiring structural stiffness, these are commonly made of long-fibre reinforced composites. Smaller pieces can be produced in short-fibre composites, composite materials with particulate reinforcement or unfilled polymers.

Intake ducts and airhorns (also called snorkels or aardvarks) lend themselves to being made out of long-fibre polymer matrix composites. In recent years these parts have been most commonly made from carbon-fibre reinforced epoxies, although before this, glass-fibre was used as the reinforcement in a polyester matrix. The form of such ducts and snorkels tends to give them some inherent stiffness, but there are important tuning effects to exploit by 'tuning' the wall stiffness of these parts, especially where there are flat areas with little stiffness owing to their flat shape.

Air filters are the next component in the inlet to be commonly made of polymers. A large proportion of race air filters, from club level to the very highest level, are made from expanded open-cell polymer foams, which are generally polyester. In fact, such filter foams are commonly made up of a number of layers with different filtration characteristics. These filter foams are very light, but often require some additional support to retain their shape.

The airbox, or airbox tray can, as the names suggest, comprise anything from a tray to a deep complex box. Again, the shape, size and stiffness of the box can have an important tuning effect on an engine. Like an airhorn, an airbox is basically a shell-type structure, and these are again made of polymer matrices reinforced with carbon fibre.

Intake trumpets (also called funnels or bellmouths) have for a number of years been commonly made from polymer materials or composites. Thin-walled carbon-epoxy composites are favoured by a number of engine suppliers, and these lend themselves to trumpets that do not have a regular circular cross-section. These can be very light components, and this is one reason why big-budget racing favours such materials.

Injection-moulded composite trumpets have also been common where quantities are sufficient to invest in the necessary tooling. The materials for injection-moulded trumpets range from short-fibre composites (commonly fabric or glass fibre) for thick-walled low-budget parts, to fine particulate reinforcement of high-budget polymers such as PEEK where thin walls and complex shapes are required. Such injection-moulded parts in reinforced top-end polymers can be competitive in terms of cost compared to carbon composites.

Other polymer moulding techniques such as vacuum casting can be competitive in terms of cost with machining, even where quite small batch sizes are concerned and when the machined shape is simple.

Some types of throttle can be made from polymers, and both butterflies and barrels lend themselves to both machined and moulded polymers and composites. The advantages are low component mass and low throttle inertia. Low inertia can be a consideration when designing throttle systems for semi-automatic (paddle-shift) gearboxes, where a crisp throttle response is required for downshift throttle 'blipping'.

For all inlet system components, their low thermal conductivity is an advantage as they remain at lower temperature than they would if made from more thermally conductive metal materials. Higher wall temperatures lead to higher heat transfer to the incoming charge. Some of the same effect can be gained from using thermal insulators in the walls of the intake tract, in order to limit the transfer of heat. Polymers and composites are sometimes used for this purpose, with composites with various fillers from glass to cotton being used. With the thermal conductivities of these insulating materials often being much less than 1% of aluminium, they are very effective in limiting heat transfer by conduction.

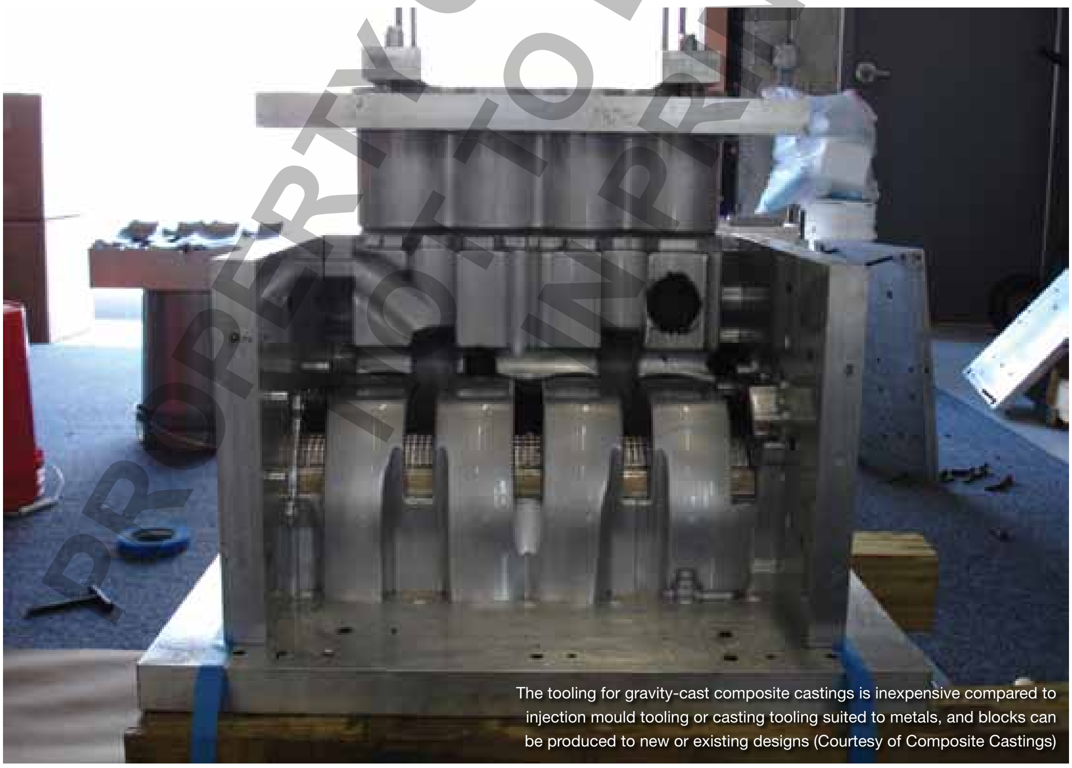
Exhaust systems

Non-metallic materials can be found in a surprising number of exhaust applications. Silencer packing is commonly made from glass-fibre or 'stone wool' which is fine fibres of extruded rock, commonly basalt.

Where race diesels require diesel particulate filters (DPF), their elements are often made from ceramic materials. Cordierite is commonly used for road applications, but has a low melting point. Silicon carbide may be more suited to race applications with very much higher service temperatures, although aluminium titanate seems to be very promising for production applications.

Beyond this, we can find the walls of exhaust silencers (mufflers) made from composites, especially carbon-epoxy, and particularly in motorcycle racing.

Ceramic-matrix composites, reinforced with ceramic fibres, have been touted as possible exhaust materials. Some of these very specialised materials can be processed by normal means, using the same equipment as for carbon-epoxy composite production, including conventional autoclaves. However, almost all the material seems destined for larger-scale users of this technology such as those in the aerospace and military sectors, with only big-budget teams likely to get a look-in at this stage. At least one Formula One team is thought to have made prototype exhaust collectors some years ago, and this year one team is strongly rumoured to be using it as part of its unusual exhaust system, the material having ▶



The tooling for gravity-cast composite castings is inexpensive compared to injection mould tooling or casting tooling suited to metals, and blocks can be produced to new or existing designs (Courtesy of Composite Castings) been the subject of public debate between teams in 2011.

Exhaust systems are commonly ceramic-coated to retain heat within the exhaust. For turbocharged engines, it is important to retain as much heat as possible within the exhaust flow, and if exhaust energy recovery is to become an important part of motorsport's drive towards increased energy efficiency, then ceramic coating of exhausts is likely to become more common in future. However, reducing the amount of heat radiated or otherwise transferred from the exhaust system to the other components under the engine cover also has value, as it improves the reliability of other components, particularly electronics, where high temperatures can cause soldered joints to fail.

Turbocharging

The role of non-metallics, and ceramics in particular, has been studied with particular zeal with regard to turbocharged engines. As stated previously, it is an advantage to have the turbine inlet flow at high temperature, and efforts to ensure this have meant that people have studied the possible advantages of ceramic port liners. This has the added advantage of minimising heat transfer to cooling water, which can allow the use of a smaller radiator; for this reason, insulation of the exhaust port can be a valid strategy for naturally aspirated engines too.

Ceramics have been used widely for turbine wheels in turbochargers. The combination of low density and high-temperature mechanical properties makes ceramics such as silicon nitride prized for rotating turbocharger components. Turbine wheels made from traditional high-temperature metals such as Inconel necessarily had high inertia owing to the density of the material, and could not offer the desired transient throttle response. Advances in ceramics mean that low-inertia turbine wheels can be produced economically, and throttle response has been much improved through their use.

Oil tanks

A look at many pictures of a modern Formula One engine will show you that they are equipped with a carbon-fibre oil tank. These are not simple 'shells' as one might think from looking from the outside, but contain many features specifically designed to control the quality and location of the oil in the tank during rapidly varying g-loads caused by cornering or rapid changes in track gradient. While the fabricator's art is not yet dead in producing these very complex oil tanks, carbon has come to be the preferred route for many engine manufacturers.

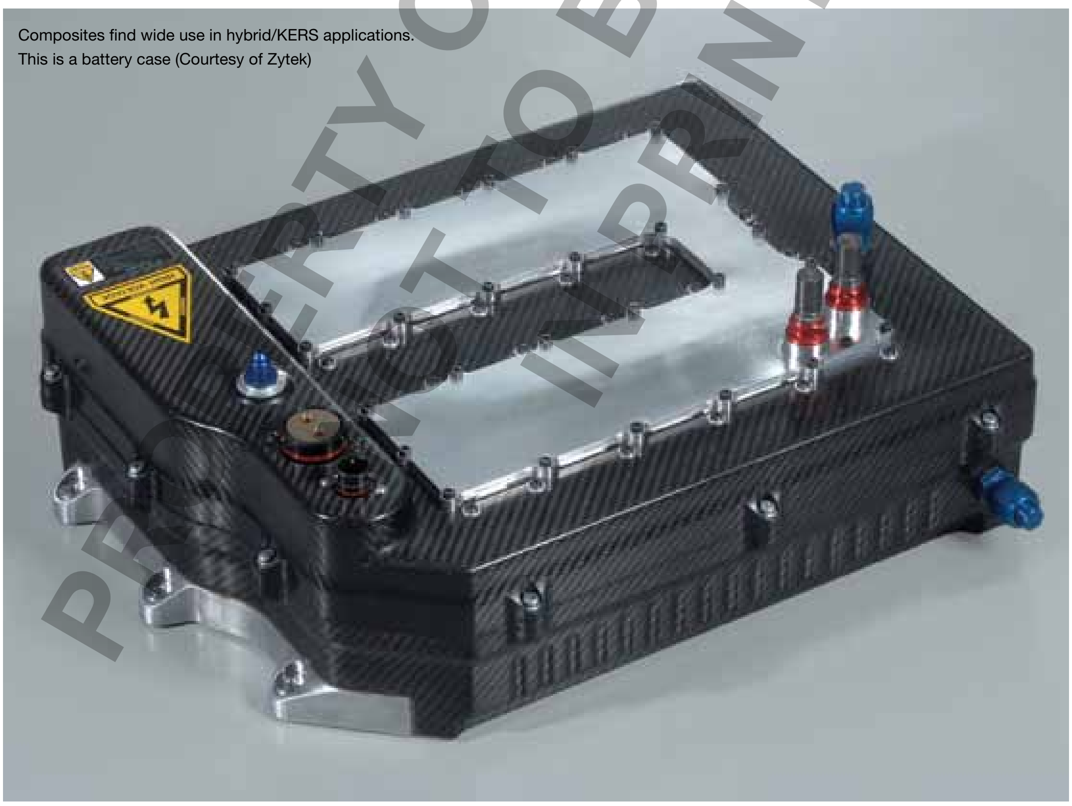
KERS

The advent of KERS systems in Formula One, which are essentially a race version of the hybrid systems found on roadcars, has increased the amount of non-metallic materials used in racing. Outside Formula One, hybrid systems had been in use in motor racing many years earlier – notably with Zytek-equipped Panoz in the late 1990s – and KTM even had a 125 cc hybrid Grand Prix bike racing at the end of 2008, apparently giving an approximate 6% boost in peak power.

There are two main types of hybrid systems being used in racing. The more common system, the electric hybrid, is based on the familiar technology of electric motors and batteries. These systems work at very high voltage, and non-metallic materials are necessary for electrical insulation purposes.

Depending on the particular application, a number of materials are suitable. Owing to their inherent flexibility, rubbers and other elastomers are used for the insulation of cables and wires of all kinds, whether high or low voltage, and different insulating materials are used in the various electronic modules. The batteries consist of many individual cells; in the case of round metal-walled cells, the walls need to be insulated from each other. In the case of 'flat' cells, these are generally sealed in an insulating polymer, and can be used with the cells contacting each other.

The cases which are used as enclosures for various high-voltage electrical modules are normally made of composites. Commonly they are an epoxy matrix composite, the fibre reinforcement generally being either glass, carbon, aromatic amide (aramid) or some other polymer fibre. Glass and aramid fibres are less conductive than carbon. Compared to glass, aramids and other special thermoset fibres have much higher specific strength and modulus. As can be seen from the table of properties of non-conductive fibres, their properties are very impressive. The properties of a high-strength steel have been



Composites find wide use in hybrid/KERS applications. This is a battery case (Courtesy of Zytek)

Properties of fibres used for reinforcement, with steel added for comparison

Material	Density (g/cc)	Strength (MPa)	Elastic Modulus (GPa)	Strength / Density	Modulus / Density
E-glass	2.55	2000	80	784	31.4
S-glass	2.49	4750	89	1908	35.7
Kevlar 49	1.44	3750	136	2604	94.4
Steel	7.85	2200	210	280	26.8

added for comparison.

Also used in racing are mechanical hybrids, where energy is stored mechanically in a high-speed rotating flywheel. We are all used to seeing metal flywheels as attached to engines, but flywheels designed for maximum energy storage rely on non-metallic materials. Such are the forces involved that filament-wound carbon-epoxy composite flywheels are the order of the day. The flywheel energy storage systems developed by Flybrid, Williams and Ricardo all rely on the impressive mechanical and physical properties of composites for their success. This year a mechanical hybrid system raced at the Le Mans 24 Hour event, and this type of system is also being developed for a number of automotive manufacturers for future roadcars.

Fasteners

Non-metallic fasteners are not something we would normally consider, but with the advent of electric-hybrid technology there are a number of applications where non-conductive fasteners are of use. Due to the fact that similar applications exist outside motorsport, there are non-metallic fasteners available as stock items in a number of different materials. There are also composite fasteners, where continuous fibres run along the length of the screw and around the helix of the thread. These are of use where the strength of more conventional homogenous polymers is insufficient, although I'm not aware of any current motorsport application for such fasteners.

Non-metallic washers are useful not only for situations where electrical insulation is required, but also where thermal insulation is important. If we imagine the situation where we have separated two thermally conductive metal components with a thermal insulator, the main path of heat conduction between these parts is likely to be the fasteners. A non-metallic washer or bush, which can be made from a polymer or composite, can be an effective means of reducing heat conduction.

Electrical applications

Of course, printed circuit boards are electrical insulators, with conducting 'tracks' printed onto them. Glass composites are commonly used for this purpose, and a number of circuit boards are required in a typical electric hybrid system, as well as in engine control units. Flexible printed circuit boards, where the tracks are printed onto a thin flexible polymer membrane, have found common use in motor racing in recent years.

Bearings

Polymer coatings on bearing shells are widely used in racing, although opinion remains split on whether they offer a real advantage. The general polymer-coated bearings available are based on existing bearings, either production-based or from a reputable bearing supplier, and these are then polymer coated by a third party which subsequently markets them for race and aftermarket applications.

At the moment, lead-based overlays on conventional metallic backings remain the order of the day in racing. It is conceivable that polymeric overlays will eventually replace soft metal overlays, and much work is being done in this development direction, with polymer overlays being available for production bearings (4). Typical polymer overlays are composite materials with a resin matrix (epoxy, phenolics or PAI) containing between 50% and 80% of solid lubricant (which itself may be a polymer) with additions of ceramics for wear resistance.

Ceramics have found increasing use in rolling-element bearings. While complete ceramic bearings are available for high-temperature industrial use, bearings with ceramic balls offer most of the dynamic advantages but are much more forgiving of shock loads and are much less expensive. Silicon nitride balls and rollers tend to make rolling element bearings run cooler for a given speed, and are more tolerant of hard particles and contaminants. These find widespread use in electric motors, as they prevent an electric circuit being completed through the bearing, which leads to rapid bearing damage. They are therefore a very relevant technology as far as race hybrids are concerned.

Ceramic rolling-element bearings are specifically banned in Formula One engines after a number of engine manufacturers ran promising tests on roller bearing crankshafts using silicon nitride rolling elements in the early 2000s. Roller-bearing cranks were once commonplace, but have largely been supplanted for multi-cylinder engines by plain bearings.

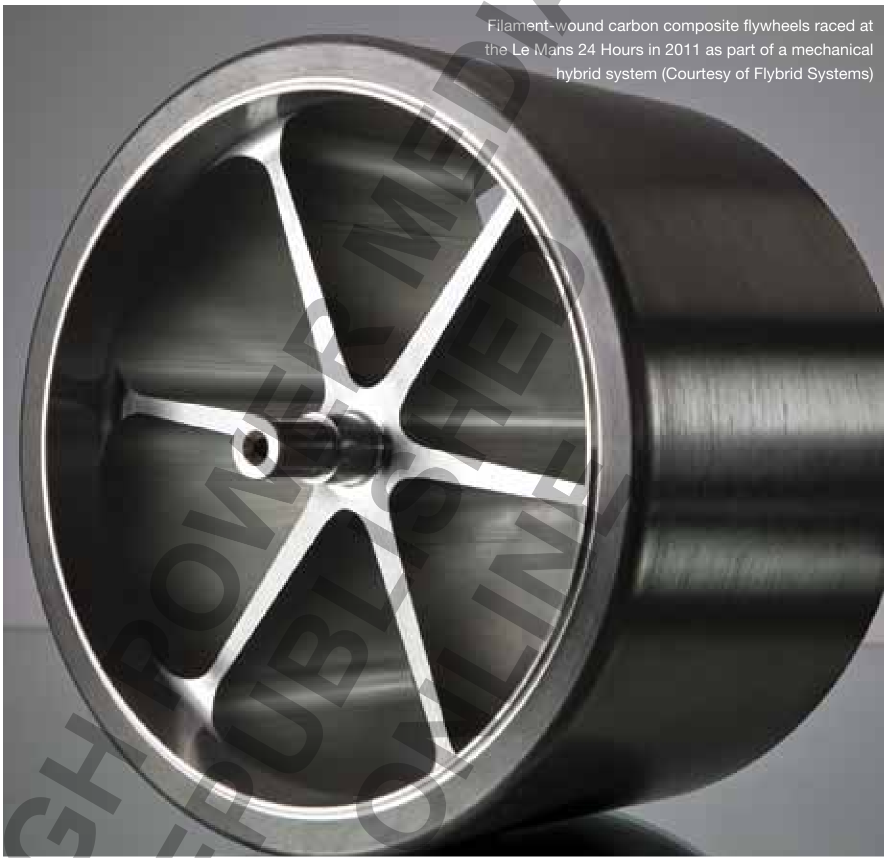
Roller bearings require very little lubrication in comparison to plain bearings; engines with excessive oil flow through plain main bearings tended to find large gains in performance when this oil flow was reduced drastically when rolling-element bearings were used. Others, with low bearing leakage flow rates in their plain-bearing engines, found comparatively small gains when testing roller-bearing crankshafts. The ceramic-element bearings were very expensive in comparison with plain bearings, and in any case still required a hardened steel shell – very similar to a conventional plain bearing – in order for the rolling elements to have a suitable surface to run against. However, for the remaining driveline other than the engine, rolling-element bearings with ceramic balls or rollers remain common.

Pressed and riveted steel cages are often replaced with polymer cages in rolling-element bearings, with PEEK being a particular favourite for this use. These offer lower friction, lower mass and lower inertia. Where high rates of acceleration and deceleration are experienced, these types of cages are favoured. ▶

Heat shields and thermal insulation

As mentioned with regard to exhausts, the management and containment of heat – specifically exhaust heat – is an important aspect of building a successful race machine. Composite heat shields have been common for a number of years. By placing a solid wall between the heat source and the component to be protected, the mechanism of heat transfer by radiation is prevented. Of course, the heat shield is now subject to this radiation and the energy has not disappeared, but in protecting vulnerable components from the effect of heat, we are seeking to improve the reliability of the car/bike/boat. Composites are a good material choice for such heat shields; they can be made with simple moulding techniques and offer low thermal conductivity. It is common to coat them with ceramic materials to further increase their thermal resistance.

For applications where we wish to minimise the effect of all heat transfer mechanisms, insulating the component in question is possible with specially developed products. These are often flexible insulation materials where metallic skins sandwich polymer fibre (commonly polyester) fillers. The thermal conductivity of such materials can be one-thousandth that of aluminium.



Filament-wound carbon composite flywheels raced at the Le Mans 24 Hours in 2011 as part of a mechanical hybrid system (Courtesy of Flybrid Systems)

Future developments

Through our fortunate synergy with aerospace and military hardware, we benefit from materials developments that suit our applications. Composites, ceramics and polymers are all subject to continuous development, and racing is a lucky recipient of the improvements. Rapid prototyping has made staggering progress, both in terms of the reduction in cost of the technology and the range of materials available. Glass, carbon and metallic-filled polymer-matrix composites using particulate filters allow us to explore the use of non-metallic materials without the need to commit to expensive tooling.

Summary

The adoption of non-metallic components in the race engine has been steady and very deliberate. It certainly hasn't happened to the extent that we might have considered looking at the Polimotor engine just over 25 years ago. The costs of changing from the typical and traditional metallic materials to a non-metallic alternative can be borne in many cases only by those engine manufacturers who supply the big-budget race series – Formula One, NASCAR, MotoGP and so on. Often the regulations don't allow anything other than a small and very specific selection of materials to be used.

At a time when road-going cars use magnesium cylinder blocks, and we have composite blocks being made available for sale for some pretty basic four-cylinder engines, is racing helping itself by being so proscriptive in its materials regulations? It is unlikely that any engine supplier would make a fundamental switch of philosophy in material selection if the rules were relaxed. However, giving them the possibility to make sensible choices to adopt non-metallic materials when their engineering and economic conditions are met is a sensible way to keep racing moving forward. It is clear that polymers (both filled and unfilled), composites and ceramics will have an increasing part to play in the future development of the internal combustion engine. Can motorsport afford to put its head in the sand? ■

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Further reading:

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Credits

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