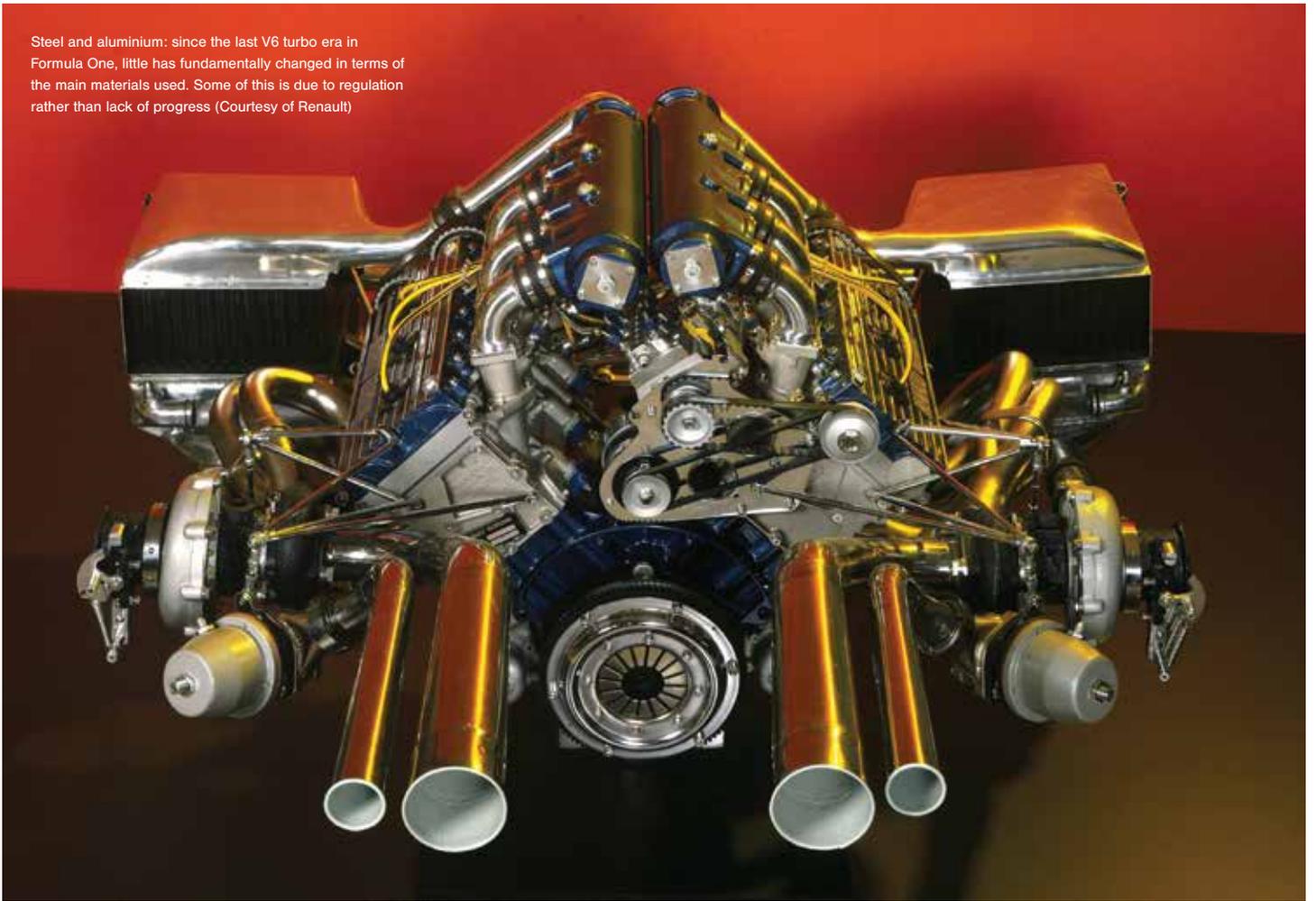


Steel and aluminium: since the last V6 turbo era in Formula One, little has fundamentally changed in terms of the main materials used. Some of this is due to regulation rather than lack of progress (Courtesy of Renault)



Material gains

Wayne Ward reports on recent advances in the manufacture and processing of metals, and the race engine applications they open up

Despite showing much promise in previous decades, and perhaps due to some stifling regulations, polymers and composites have not offered the revolution in engine and transmission materials technology that was hoped for (or perhaps feared in some quarters). In terms of monocoque chassis construction, however, composites have brought about a complete transformation in how racing teams think about materials and how they design and make racing chassis.

Metals are still very much alive and kicking though. Moreover, they have shown very rapid development, and not only in terms of the number of materials available; new types of materials are on offer commercially and new manufacturing methods have been able to improve the strength characteristics of existing materials. In the past few years we have also seen the rise of additive manufacturing (AM), which is causing designers to think in an entirely new way about design for manufacture. It may also in the medium term lead to an improvement in conventional materials manufacture.

Motorsport has conventionally played second fiddle to aerospace and defence industries in terms of materials, and as we shall see, in some areas it continues to do so. Motorsport 'inherits' new materials from those sectors, so it benefits from being offered new, improved and – importantly – tested materials. However, motorsport development cycles are incredibly short compared to those in aerospace and defence, yet precisely because of this it can be relevant in the development of new materials and processes. In fact, there are a number of relationships between high-budget motorsport teams and large aerospace manufacturers, and a number of joint ventures where motorsport companies are involved in aerospace and defence projects.

Simplicity in regulations

On many occasions, motorsport's rule-makers have taken a very simplified view of the world. However well-intentioned the rules on materials are, they often don't reflect reality – or, more precisely, economic reality, which is often the reason for the existence of a

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particular rule. In the eyes of many rule makers, there are metals that are classed, or thought of, as being ‘exotic’. As a consequence, they are imagined (often incorrectly) to be hugely expensive.

Let us take two examples of metals that are often excluded. First, magnesium alloys have long been disallowed in Formula One engine construction, even though they are allowed in the construction of the car. Magnesium is commonly found on some ordinary passenger cars and motorcycles, and if the regulations were relaxed then the FIA ought to realise that there would be very little danger of people spending a lot of money following the lead of BMW with its passenger car magnesium cylinder block. However, we might well replace a lot of unstressed covers that are currently made from aluminium (or even polymers) with magnesium: it can make engineering and financial sense to do so. Instead though there is no limit on the composition or cost of aluminium or polymer materials in the rules, with the result that a number of the materials that are within the rules are far more expensive than magnesium.

Titanium is another obvious example of a material that has been outlawed for some components (fasteners being one example) in big-budget series, but we then find titanium fasteners used by some relatively low-budget motorcycle teams racing in national championships. It would be naïve to think that Formula One engines are assembled using off-the-shelf cap screws, and there are plenty of expensive, carefully designed fasteners that are made from some very expensive tool steels and superalloys.

Teams have a budget, and they will spend it wherever they see the greatest benefit. As already mentioned, part of the charm of motorsport, as far as other companies and industries are involved, is the rate at which development iterations take place. Intermetallics (more of which later) are of real interest to car manufacturers, but this class of materials is now effectively outlawed in the race series that were using them. In this case, as with many others, motorsport’s opportunity to help the wider automotive industry with development is curtailed.

Manufacturing and processing developments

Many of the recent developments in metallic materials have come about through changes in their manufacturing and processing. For example, powder metallurgy (PM) methods, where finely divided powder is heated and compressed to form an ingot, rather than traditional casting methods, have been instrumental in improving the mechanical properties of materials, as they offer the prospect of much-improved fracture toughness and fatigue strength, both of which are strongly influenced by maximum defect sizes in components. While defects often show up as mechanical damage or cracks emanating from a design feature that has created a significant stress concentration, there may also be non-metallic inclusions in the material.

With their recent focus on ever-smaller powder particle sizes, PM methods offer direct control over maximum internal defect sizes. They have been most widely applied to premium tool steels since, in addition to controlling defect size, they also offer the prospect of being able to produce more highly alloyed steels than is possible with conventional melt-state processing.

There is no realistic alternative to steels for highly stressed gears. Development of increasingly fatigue-resistant grades ensures that steel will continue to dominate for such applications (Courtesy of Bohler)



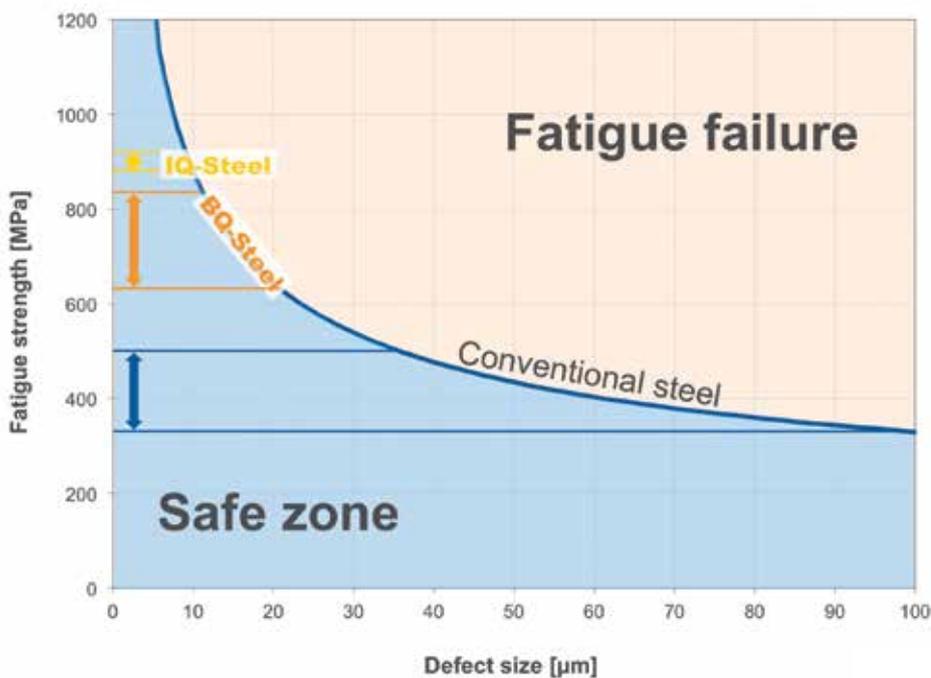
The take-up of AM meanwhile has enjoyed a huge boom in the past few years, and there is great excitement over the ‘rise of the makers’ as people clamour to get 3D printers of the fused-deposition modelling variety at home. In industry, AM is huge business, and investment in producing metal parts by building them from powder or wire is attracting attention from all quarters. It has the potential to completely replace the current conventional manufacturing routes – it is, in modern parlance, a ‘disruptive technology’.

A key factor in making AM a success will be that, for the methods based on sintering powder to form complex bespoke components, it will need to keep pace with techniques for manufacturing bulk materials. It needs to ensure repeatable standards for its materials, both in terms of ‘cleanliness’ – the amount of impurities in a material – and maximum defect sizes. Companies producing powder stocks for their own PM production of bulk materials in bar or plate form might find customers in the shape of the users of laser-sintering machines, and such economies of scale may lead to cheaper PM materials and higher quality AM components. A side-effect might also be to vastly increase the range of AM materials available. One company quizzed for this article said it is developing new materials specifically for AM, rather than simply providing powdered versions of existing metals.

Steels

Steel continues to occupy a very strong position in motorsport engine and transmission manufacture – for highly stressed components there is little choice. While cast iron is used for some crankshafts and camshafts, the most highly optimised components are made from billets of high-quality steel: there is a wide range of steels, and the best of them are very strong indeed. Their only realistic rivals in terms of strength are perhaps superalloys, but these are incredibly expensive to buy and to use to make components.





Inclusions and other defects have a strong influence on fatigue strength. Efforts to control defect sizes and numbers have been rewarded with much-improved steels (Courtesy of Ovako)

With regard to steel, there have been two main avenues of development – PM and improved cleanliness/defect control.

PM manufacturing methods have produced two main groups of materials here. The first consists of steels which maintain the same basic composition as existing steels (some of which are very old grades, such as H13) but which derive benefits from the reduction in defect size brought about through the use of powder. There are continuing benefits to be derived from the use of the finer modern powders, and the original PM tool steels produced commercially are probably not offering the maximum benefit achievable from PM processes. However, as powder particle sizes become smaller, so the benefits of going further still will be subject to diminishing returns.

The second group are the highly alloyed materials that cannot be produced reliably through conventional routes, and allow development trends that had reached a compositional ceiling to continue. For example, steels are being produced specifically for increased stiffness or reduced density, which would be difficult or impossible to make using conventional methods. In conventional melt-state processing, there can be a level of ‘segregation’ of alloying elements during solidification, leading to an inconsistent level of certain elements throughout the structure of the material. Where high levels of alloying elements (including carbon) are used, a coarse network of inter-granular carbides is formed, and extra processing is needed to improve the microstructure to make it more homogenous and better refined.

However, it is virtually impossible to completely eliminate the effects of segregation, and the higher the carbon and alloying content, the worse the problem. Yet by producing atomised powders of the same troublesome material, which are subsequently mixed and formed into fully dense solids through canning and sintering, the highly alloyed materials are freed from segregation, and they also benefit

from having a limiting maximum defect size as a result of the atomisation.

The development of ever-cleaner steels is very important, as it has a major impact on fatigue strength. Sulphur and phosphorous are both frowned upon where high-strength steels are concerned, and while sulphur is sometimes added to steels to improve machinability, it can do more harm than good. Both elements are very reactive, especially so with reactive metals that might be present by design or as impurities. A company I once worked for had to scrap a batch of camshafts because it had mistakenly been supplied with material that was of the ‘improved machining’ type. A large sulphide inclusion which had formed in the material had subsequently been turned into an extremely long defect during the rolling process, and a number of bars were affected.

Cleanliness in steels is markedly improved by re-melting processes, and re-melted steels command a premium price because they offer fewer defects and hence improved fatigue strength. There are various re-melting processes; those you will commonly see mentioned are ESR (Electro Slag Re-melting), VIM (Vacuum Induction Melting) and VAR (Vacuum Arc Re-melting). Double re-melted steels are offered as the ultimate in terms of cleanliness – that is, the lowest percentage of impurities – and they have been shown to offer improved fatigue strength over single re-melted materials. Double re-melted steels are often used for highly stressed crankshafts.

There has been a great deal of work to reduce the number and size of inclusions or defects in steels without having to use re-melting process. One company I spoke to has improved all stages of the production process to produce very clean, homogenous steels which have the same benefits of re-melted products. Through careful control of ladle metallurgy (as in a careful selection of ‘ingredients’), increased desulphurisation, increased degassing, ingot casting in an inert atmosphere and increased soak times at temperature have reduced defect size and anisotropy.

Anisotropic materials are ones where the strength in different directions is markedly different (for example the longitudinal and transverse directions in rolled products). If the fatigue strength in the transverse direction in a plate is half of the fatigue strength in the longitudinal direction, you need to be very careful how you cut your components, so that the loads are taken in the strongest direction. By contrast, isotropic quality (IQ) steels with low defect sizes show virtually no difference in fatigue strength between longitudinal and transverse directions. In addition to component strength being less dependent on direction, it means that certain parts which have complex stress cycles can be made lighter.

In a number of applications we require rolling element bearings, mainly for transmissions, but increasingly they are being used in hybrid systems. The traditional steel used for such components would

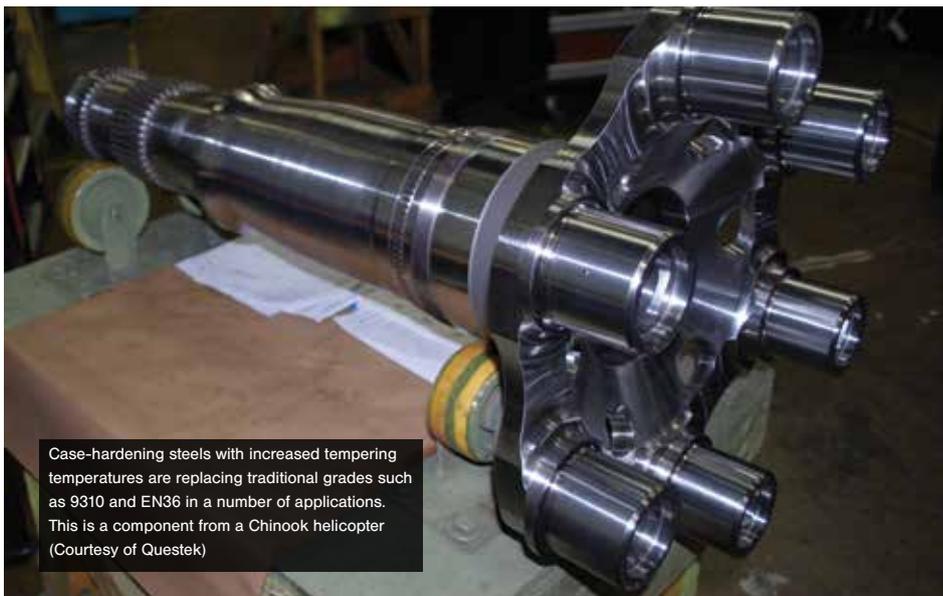
be something like 52100, a carbon-chromium steel which can be hardened in moderately deep sections and which shows good wear resistance. To improve resistance to rolling contact fatigue, there are both single re-melted (VAR) and double re-melted (VIM-VAR) variants of 52100 available.

52100 is said to be suitable for use at up to 200 C, and although we may never intend our engines or transmissions to become that hot, there are reasons why we may want to consider a different material. Although we may not soften the bearing material at temperatures below 200 C, there are changes in the material over time when operating at temperature. Standard bearing steels can suffer from a lack of thermal stability, and temperatures as low as 130 C can cause problems, but only over extended operating periods at this temperature, as shown in the paper on medium carbon steels in the publication by Hoo and Green (1).

In this paper, 52100 is compared to case-hardening steels used for large bearings. Case-hardening steels for large bearings have only a small volume of hardened case, and high ratios of the volume of the unhardened core to the hardened case prove valuable for avoiding thermal instability. While the manifestation of thermal instability in 52100 is not a rapid one at 130 C, we should note that the local operating temperatures for the bearing are almost certainly greater than we anticipate from measuring temperatures in our engines and transmissions, and may be high enough to cause dimensional changes in the bearing races.

To avoid thermal instability, loss of hardness with increasing temperature and to improve wear resistance in a rolling element bearing, there are alternative steels. The molybdenum high-speed tool steel M50 is one that is commonly used for aero engine bearings, and its use is largely the result of a decision taken by the US government several decades ago to avoid the use of bearing steels containing tungsten, as it feared there would be a shortage of it. M50 might otherwise therefore not have found favour compared to the M2 and 18-4-1 steels which had been successfully used, but which contained tungsten. Alternatively, steels alloyed with nitrogen, such as Cronidur 30, have proved successful in avoiding all the problems mentioned above. According to Hoo and Green, these steels can be heat treated to induce residual compressive stress in the surface or to improve hot hardness, thereby extending the operating range above that of M50.

In terms of case-hardening steels, there is a development trend towards those with higher tempering temperatures. In aerospace, these are finding a growing number of applications, replacing steels such as 9310 and EN36. Higher tempering temperatures offer the possibility to use a number of coatings whose process temperatures would soften a material such as EN36. One company supplying this type of steel has noted that some race teams are running transmissions with less oil because of the greater temperature capability of these steels.



Case-hardening steels with increased tempering temperatures are replacing traditional grades such as 9310 and EN36 in a number of applications. This is a component from a Chinook helicopter (Courtesy of Questek)

Soft magnetic materials

The demand for 'electrical steels' in racing has grown significantly in only the past few years, although they are perhaps more correctly termed iron alloys rather than steels. We are now in an era where hybrid propulsion is an important part of the performance of the racing power unit in both Formula One and top-level endurance racing, and pure electric racing is firmly established for motorcycles and cars. The TT Zero race on the Isle of Man goes from strength to strength, and top riders compete on prototype machinery, while the Formula E car series has started with a number of high-profile names involved as drivers and team entrants.

While electric motors are not the only viable solution for hybrid propulsion, they are the most commonly used. In terms of their construction, the stator consists of laminations stacked in an outer case, with the electrical coils wound around teeth produced on this stack. Electrical steels are not used for structural purposes but for their electrical/magnetic properties, and energising the coils turns the 'soft magnetic' teeth of the laminations into magnets, which can therefore be turned on and off at will. The accurate timing of these electromagnets being switched on and off, acting on the permanent magnets attached to the rotor, produces a torque.

Soft magnetic materials have a property known as a magnetic saturation limit, which is basically a measure of the magnetic flux beyond which the material is not further magnetised: a high saturation limit gives a more compact and efficient motor. Several kinds of material are suitable here, but pure iron, iron-nickel, iron-silicon and iron-cobalt alloys are all used. In general, people will seek out the material with the highest saturation limit, and the best electrical steels have a saturation limit in excess of 2.0 Tesla. Another important factor is the thickness of the individual laminations which, combined with a surface that offers some degree of electrical insulation between individual laminations, means that electrical losses in the steel, known as eddy-current losses, are minimised. These materials can often lack ductility though, so producing them in ever-thinner sheets is not easy, but the development of materials with increased saturation limits in very thin sheets is ongoing. Such materials offer improved efficiency and smaller, lighter motors for a given level of output. ▶



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