Con rod in 'Bolts Down' configuration (Arrow Precision)

Vital connections

Wayne Ward examines the latest developments in the technology of racing engine con rods

The con rod is an often overlooked component – whilst it plays a very important part in the fundamental power conversion mechanism of the engine (there are very few realistic alternatives, and none which has been used in a series production or successful racing engine), nobody really sees it as a component which produces power. The main purpose of the con rod is to turn the translation of the piston into a more suitable motion for producing power. Man had already gone a long way toward perfecting the harnessing of chemical energy to produce motion in the centuries before combustion engines of any type were invented. The main purpose of these machines was warfare related, and in a visit to any castle or similar fortification one will generally see rows of these simple machines called cannons, another example of an early internal combustion machine.

However, in trying to determine the current state-of-the-art in racing engine con rod design we turned to industry experts to tell their side of the story. *Race Engine Technology* spoke to producers of con rods across many racing formulae – endurance, motocross, superbike, MotoGP, Formula One, NASCAR, drag-racing and others in compiling this article.

Those involved in turning a road-based engine into a real racing engine will often look at the production con rod with some disdain, and substitute it for a more suitable alternative, which is more carefully designed, made from better materials and will be much more durable. It is probable, but by no means certain, that the replacement con rod will be somewhat lighter than the production con rod. It must be said that there have been some very nicely made production con rods in recent times and certainly there are examples which would be suitable for very serious racing without any modification whatsoever. These parts are, however, generally confined to limited-production models which the manufacturers can reasonably expect to be involved in racing at some point in their lives.

Certainly the performance gains that we would find from fitting a new con rod in isolation are likely to be marginal at best, and might need a lot of testing to be sure that there is really a gain. Unless the preceding con rod had a very fundamental design problem, it is probable that any gain would be within the error of the dynamometer. Indeed, to get an answer which we can trust might require a special piece of test equipment which is much more sensitive to small changes than using an engine on a dynamometer.

So, once we have a con rod which is sufficiently durable for our racing application, what further incentive is there to continue the drive to produce a better con rod? Some might say that there is very little incentive but, in race series where there is free development (such as the old version of Formula One), the con rod is constantly being examined in light of improvements to associated components which influence the loads on the con rod.

In order to understand this, we must first examine the place of the con rod in the engine, what affects the loads upon it, how it transmits the loads that it is subjected to.

Con Rod Basics and Operating Environment

The con rod provides the connection between the piston at one end, and the crankshaft at the other end. Owing to the fact that the ends of the con rod are generally of noticeably different dimensions to each other, these have become known as the small end (or little end) and the big end. The small end is that part of the con rod providing the pivot between it and the piston, and the big end of the rod provides the pivot between it and the crankshaft. The French refer to the ends of the rod as the *pied de bielle* (foot of the rod) and *tête de bielle* (head of the rod). Strangely, the part of the con rod which the French refer to as the 'head' of the rod is the end connected to the crankshaft and therefore further away from the top end of the engine than the 'foot'.

The load due to the pressure imparted to the combustion-facing surfaces of the piston is transferred to the con rod via the piston pin (often referred to as a gudgeon pin or wrist pin). From here, the load is transferred axially along the con rod to the crankshaft. Owing to the rotating motion of the crankshaft power can be taken from the engine for any number of uses. However, in general, we are interested in this power being used to transport the engine, chassis and driver as swiftly as possible around or along a track.

The connection to the piston pin can, as far as the con rod is concerned, take one of three options, namely those (a) having the piston pin fixed in the con rod, (b) loose and therefore able to rotate within the small end or, (c) fixed in relation to the piston and therefore rotating within fixed limits. In general, for racing applications, we will find that the pin is able to freely rotate within the con rod.

What we can draw from the very simple explanation above and the description of the options for connection between the piston and the con rod is that we will, at least, need to provide a bearing at the big end and quite probably a bearing surface at the small end also.

In four-stroke racing engines we will, in most circumstances, find that we have a single-piece crankshaft, and therefore in the design of the con rod, we must provide a split so that the rod can be fitted to the crankshaft. This split requires careful consideration in design – we must ensure that the joint is fastened with sufficient force to remain together during normal operation and foreseeable 'misuse', and that the two 'halves' are located well enough to ensure that the bearing can operate properly. In con rods for two-stroke engines, we will in many cases find that the crankshaft is split, allowing the con rod to be a single piece with no discontinuity at the big-end.

For any given crankshaft angle, α after top-dead-centre, there is an angle of articulation of the con rod, ß which depends upon the geometry of the mechanism, namely the throw of the crankshaft (equalling half of the stroke), r and the length of the con rod, l, as measured between the centres of the small-end and big-end bearings. In view of this and then performing a little mathematical manipulation, we can see that the angles are related thus:

$$ß = \arcsin [(r/l) \sin \alpha]$$

The result of this relationship is that, for a given engine stroke, the fitting of a shorter con rod increases the maximum angle of articulation, and also the angle at any given piston displacement. There is a resultant increase in the thrust load between the piston and the liner.

In terms of the operating environment of the con rod, it is able, in four-stroke engines at least, to carry out its business in quite a comfortable environment. The crankcases are generally sealed so that outside contamination cannot enter, and the only fluid which is intentionally present is lubricating oil.

Requirements in Design

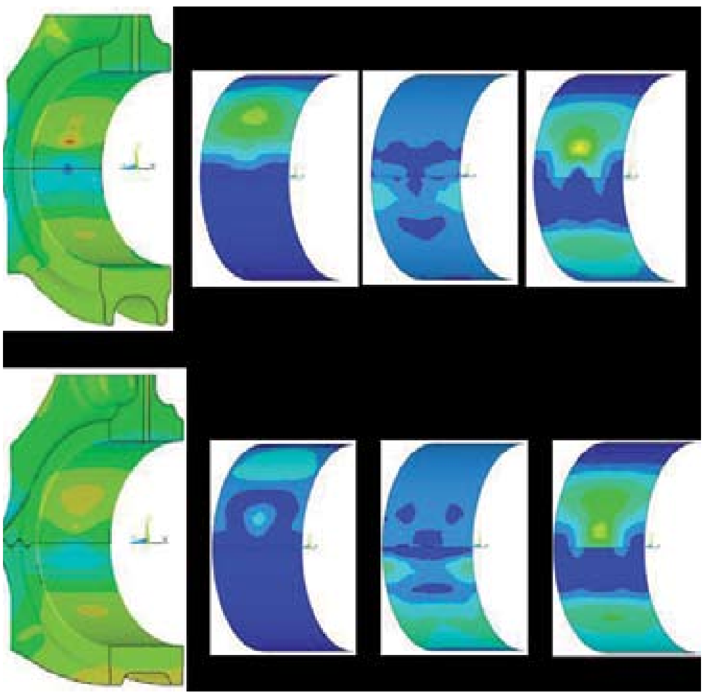
In addition to fulfilling the primary requirement of load transmission, there are a number of other requirements which the design of the con rod must take into account.

We have already mentioned that the con rod must make provision for bearings. At the small end, in general, we will not think that the small end bearing will be able to operate in an essentially dry condition, and so we will need to make provision for the supply of lubricant to this bearing. In a four-stroke engine this bearing has traditionally been a pressed-in part, ordinarily in a bronze material. In a two-stroke engine, it is normal for there to be needle roller bearing used in this application. However, this is not always the case.

At the big end, the two-stroke engine will ordinarily use another needle roller bearing. In the case of the four-stroke con rod, the bearings are provided by separate components (the bearing shells). The bearing here is a journal bearing, and key to their successful operation is to maintain a film of lubricating oil between the crankshaft and the bearing shells. There are a good number of technical papers and books which the keen student can study to apprise him / herself of the basics of the design.

In the case of the two-stroke con rod, we can see that we have already begun to make some demands on the material of the con rod; it must be hard enough to support the operation of a needle roller bearing.

In addition to designing the con rod for the correct length and ▶



FEA is increasingly important: here fretting is analysed (Pankl)


Most rod manufacturers prefer forgings for steel rods (Auto Verdi)

providing bearings and lubrication, we also need to consider strength and stiffness.

In terms of strength, we again have to design the con rod carefully as there are a number of stress concentrations in the con rod which the rod designer must pay special attention to. What we can generally say though is that the main shank of the con rod is not very highly stressed. If this is the case, why is it that more material is not removed and the con rod made consequently lighter? Much of the answer lies in providing sufficient stiffness.

In terms of stiffness, we can consider this in three conditions: tension / compression, bending and torsion. The basic choice of material, and its distribution, affect the stiffness. In each case, if we are to consider a truly optimal design, we need to consider these carefully.

If we look at how the stiffness of the con rod in tension and compression affects the piston motion, we can understand that, under conditions of maximum deceleration, there will be a tendency for the piston to carry on in the direction of travel. A con rod of lower stiffness will therefore, as engine speed increases, increase the stroke of the engine. This cyclic effect of shortening and lengthening of the con rod increases proportionally to the square of engine speed, and it can be managed, some believe, to provide an advantage. Certainly, its effect is to increase stroke and therefore engine capacity. However, it affects valve to piston clearance and therefore we have to match the requirement of this against the stiffness of the con rod.

In terms of torsion, we can imagine that, holding the big end of the con rod stationary and providing an angular displacement of the piston and then releasing it, the rod and piston behave as a torsional pendulum system, with the piston acting as an inertia and the con rod acting as the flexible element. Obviously, when studying this at school, we generally only examine the case of a massless cord with an inertia attached. The case in a racing engine is complicated by the changing stiffness of the rod section (section modulus) along the length of the con rod and the fact that the rod has its own significant inertia. However, the fundamentals are the same and control of the torsional stiffness of the con rod is important for a number of reasons. Of those we spoke to regarding racing con rod design, some viewed this as being of fundamental importance and it is thus carefully controlled in the process of con rod design. The main object of 'tuning' the torsional stiffness of the con rod is to alter the natural torsional frequency of the system so as to avoid having a torsional resonance in a critical area of the operating range of engine speed. If a con rod manufacturer asks you for data concerning engine operating conditions and the piston inertia, he will, in general, be trying to help you by designing the con rod so that any torsional resonances will not prove harmful.

One important design consideration, for split four-stroke con rods in particular, is how best to keep the two parts of the con rod in correct alignment. There seem to be four distinct schools of thought here – ring dowels, dowel pins, location diameters on bolts, and serrations. Ring dowels are hollow location pins which are concentric with, and slightly larger than, the con rod bolts.

Ring dowels seem to be the most popular – certainly they are attractive in terms of their stiffness, and the tooling used to produce the holes is larger and thus more robust, which means less reliance on constant inspection of components and tooling, and more time spent producing con rods. However, ring dowels by necessity force the bolt centres further away from the centre of the big-end bore, and there is a consequent increase in rod-bolt stress.

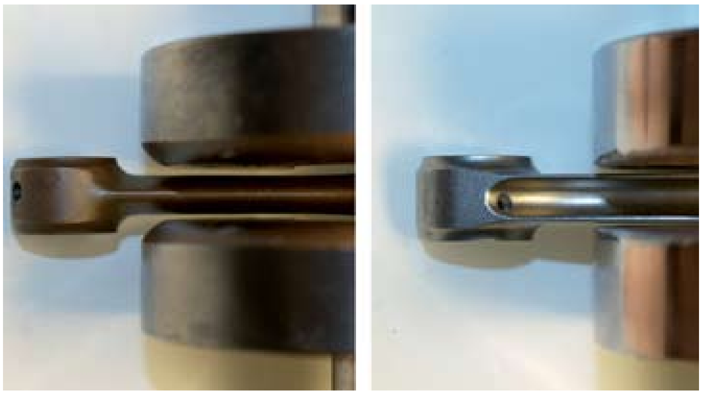
By having separate small-diameter dowel pins, we can place the bolts as close to the big-end bore as possible. Whilst decreasing stress on the bolts, this has two other advantages. The narrower con rod which is possible allows it to pass through the bore when installing con rods in heavily uprated small-bore engines. In 'V' engines, it can give the opportunity for slightly lowering crankshaft centreline height to the floor, and this explains why it was used in Formula One when this kind of development was allowed.

Fasteners with integral location diameters, taking the place of ring dowels, despite their simplicity, seem not to be very heavily used by current con rod manufacturers. This may be because, if they are close fitting, they introduce extra friction into the fastening procedure.

Perhaps though the best form of location is the serration. However, it has the penalty of being the most difficult to produce. These features are very stiff indeed and require no holes or separate components. They also promise lower levels of fretting damage at the joint face. A small number of very close-fitting serrations are widely used in Formula One, and some con rod manufacturers have their own ▶

Steel con rod (Carrillo)

Knife profile rod (left) shown in between crank webs compared to H beam rod (right) (Falicon)



particular take on this concept. I didn't speak to anyone who mentioned that they are producing 'cracked' split-line con rods, as have become common on road engines in recent years.

We come then to the most widely-debated of all design considerations concerning con rods, and that is what beam shape is best. You need not read any further if you expect the debate to be settled here – those that fall solely into one of the two camps seem quite happy that they have the best design for their application. Some choose I-beam because it is easier to manufacture, and some choose H-beam for the same reason! There are a majority who have a preference for H-beam in circuit racing, and some seem to have specific experience with certain types of engine which make them choose this type of beam. It should be noted that there are a good number of con rod producers who produce both styles of rods and some that don't express a very strong opinion.

From my own Formula One experience, I have seen both styles used and, at this level, it would be fair to say that some of the con rods used cannot be viewed as being either H-beam or I-beam, but a very-well optimised hybrid of the two styles, sometimes incorporating other features. Certainly they are specifically optimised for the running conditions and other design features of the particular engine.

There are other styles of rod-beam used, ranging from a 'knife' profile, preferred because of the aerodynamic shape, a cruciform shape, and one with a triangulated beam section with a series of through pockets.

All we can say with respect to the form of the con rod beam is that there is no single correct answer, but a number which are correct enough to be successfully used. Long may the debate continue!

Materials

The people that we canvassed for this article represent a good selection of con rod manufacturers who supply every category from grass-roots club racing in modified road cars to those supplying Formula One (both now and during the period when engine development wasn't stifled) and other categories with liberal rules.

Still, by some margin the most widely used material class seems to be steel. Steel seems still to be the choice for those upgrading from road-spec con rods to race con rods. Our various contributors felt that the grades that they use offer a good combination of the mechanical properties that they feel are important, with consistent quality. Familiarity with a material is not to be underestimated, as developing products in a new material, especially if trying to compete against a highly optimised design in a known material can introduce problems in manufacture and consequently with reliability. One of the main reasons cited as an advantage for steel is its high modulus compared to other materials which are used. With a modulus of over 200GPa, it provides for stiff bearing supports at each end of the con rod, and a stiff rod shank. Certainly some very experienced people went as far as to say that modulus is much more important than strength when considering con rod design. The steel grades 4340, 300M or their European equivalents seem by far the most popular, although there are some others used, and certainly con rod manufacturers often have a high-strength alternative for special applications.

The majority of the con rod manufacturers that we spoke to used a steel forging as the starting point of their rod manufacturing process, with few opting to machine from billet. Some either didn't say or declined to mention if they used forgings or billets.

Titanium seems to be the next most popular material, and it has for some years now been a very popular choice. It should be remembered that it has now been over two decades that titanium rods have been used in series production road vehicles. A small number of high-end road cars including the Corvette Z06 now use titanium con rods and they have been used selectively in road motorcycles for some years now. Honda pioneered the way with the RC30 / VFR750R of 1987, followed swiftly by Yamaha with their OW-01. The main advantage which titanium offers is that of low density, typically being more than 40% lower than a steel alloy. However, it also comes with a correspondingly low stiffness; in fact it will typically have a specific stiffness (or more correctly called specific elastic modulus) which is approximately the same as a typical steel alloy. The low stiffness has some benefits in terms of the ability to absorb longitudinal shock loads, and the maximum loads experienced by other components may be less in an engine with Ti rods. A similar situation exists with other materials (see later). By a large majority the most popular alloy used is Ti-6Al-4V which, as the name suggests contains 6% of aluminium and 4% of vanadium. There are a number of titanium alloys which might seem to be a good alternative to this alloy, but one of the main advantages of this alloy is that it is readily available, in high quality from a number of stockholders and producers. Other alloys, whilst seemingly more suitable in terms of mechanical properties are only intermittently available to small-order customers, may be on long delivery times, and quite possibly only available from a very small number of producers. Owing to the large quantity of high quality Ti-6Al-4V produced, it is also the most economical alloy available. I have been made aware of other titanium materials being actively investigated for high-end racing applications, but I am not able to mention the specific grades here.

It is not uncommon for titanium con rods to be produced from billet material rather than a forging, and various methods are used to produce the basic shape of the blank. With material prices being so high compared to steel, people are naturally reluctant to buy in rectangular blocks for machining which result in a large proportion of scrap material in the form of swarf, along with the time taken to machine the basic shape. There are a number of technologies whereby a blank can be produced from a piece of plate material with comparatively little scrap yield when judged against machining; chief among these methods among those companies canvassed seem to be water jet cutting and wire-cutting (electro discharge machining). Forged titanium con rods don't seem to be as popular as those produced from wrought materials, and both forged and wire-cut blanks have been used recently in Formula One.

One point worthy of mention is that there exists the possibility to produce an optimised con rod in a steel material which is almost equal in mass to an optimised titanium con rod. The material used is not a conventional rod steel, but is a special very high strength grade, and Formula One con rods have been produced and tested very successfully. I have been lucky enough to have been able to see some of these components 'in the flesh' during the development phase and it is possible that they have been raced successfully. How light the titanium con rod would have been with equal development effort is not certain – an expert estimates perhaps a maximum of 10% lighter.

Outside of these two classes of material, in circuit racing, there is very little market share. As has been alluded to in a recent *Race Engine Technology Monitor* (4) article, MMC materials have found a niche as a con rod material, and after some development, it has been found that, in the particular application in question that it is possible to run this rod without any type of bearing in the big end!

One manufacturer confirmed that they have successfully run a titanium-aluminide con rod for race applications, but added that this material is no longer used owing to its prohibitive cost. It was a high-revving four-stroke bespoke race engine, but the supplier declined to be drawn further on the exact series.

In drag-racing, and certainly at the higher-output end of the sport, aluminium is the material of choice. Chosen specifically because of its ability to absorb shock loads, it is felt that this property, a function of the low modulus of the material, is important in protecting the bottom end from the worst abuse that the combustion in these super-powerful engines can throw at it. Coatings and shot-peening are not universal with aluminium con rods, and polishing is felt to be a worthwhile final production process. Aluminium as a racing material relies on the fact that the drag-teams are disciplined in replacing parts that have reached their service life.


Steel con rod (Auto Verdi)

Aluminium was a popular choice for con rods many years ago for road vehicles, and it was particularly widely used for motorcycles.

We should mention that more than one attempt has been made to run fibre-reinforced polymer composites with varying degrees of success. I have heard more than one story describing the attempt to apply this material (carbon-fibre reinforced plastic) to motorcycle engines with little success, and at least one Formula One engine manufacturer has invested time and effort into the design, manufacture and testing of a con rod. There is some good anecdotal evidence that this was run in testing, maybe even during a race weekend, but with disastrous results. It would seem that possibly the only real success of a fibre-reinforced polymer con rod was some years ago in the pioneering and adventurous Polimotor racing engine raced in the mid 1980s in America. The matrix was a poly-amide-imide material called Torlon, and the engine ran fairly successfully in GTP Lights with some top-five race finishes.

Coatings

There are a number of coatings used in the manufacture of con rods. For a long time now it has been common to apply a hard-metal layer to the thrusting faces of the con rod where it contacts other rods or the crankshaft thrust faces. Typically this has been something like a metal-sprayed molybdenum alloy. Although this is still a perfectly valid method, it has to a large degree been supplanted by the thin modern engineering coatings. Chromium nitride (CrN) is a popular choice for this application. DLC type coatings have been and are still applied for various reasons, both in trying to avoid a specific material compatibility issue in the case of titanium con rods, and by those trying to dispense with the services of the big end bearing on steel rods.

Besides the hard-coatings, a minority of con rod manufacturers offer an oil-shedding surface treatment in an attempt to keep the con rod free of oil. When the fast-moving rod comes very close to other components, high-shear stresses in the oil lead to viscous losses which can be a significant portion of overall engine friction losses. Basic versions of these coatings have been offered for many years, but we are aware that the technology is more advanced now and may offer an advantage.

One coating supplier that we spoke to is able to offer a coating on titanium con rods which would allow it to run without a pressed-in bush.

Manufacturing

Everyone that we spoke to in producing this article relies heavily on CNC milling to produce their con rods. The capabilities of modern CNC machining mean that we have achieved that most laudable of combinations – low price and improved quality. Lately on-machine probing has lead to another step in improved quality and lower scrap rate – another new technology which, aside from initial investment, can only be viewed as positive.

As previously mentioned, there is a split, mainly along material lines as to the method used to produce the blank, with steel con rods generally being made from a forging.

▶

Fork and Blade con rod (Carrillo)

Lubrication

Whilst we can all appreciate that for the four-stroke engine with bearing shells, or indeed those brave enough to run without bearing shells, we need to provide positive lubrication to the con rod via drillings in the crankshaft. Where opinion differs is the necessity in providing a controlled flow of oil to the small end. Some manufacturers do this simply because it is a customer request, some do it due to specific analysis or on the basis of experience, and others do it to provide an additional source of cooling to the top of the con rod, thus precluding the need for a spray-jet to do the same job. The advantage of using the con rod to do this job is that the coolant flow is directed to the area in need and the cooling is thus done more efficiently with less oil flow which then needs to be dealt with in the crankcase. It should be noted that in some rare applications, the rod doubles as a spray-jet with small drillings connected to the big end aiming oil at certain areas underneath the piston.

At the small-end, most four-stroke con rods are fitted with a bronze bush, although many of those who helped in the compilation of this editorial now consider that this can be dispensed with in the case of steel con rods. However, they expressed the caveat that if this is done, regular engine strips, inspection and replacement are necessary. The reader is referred to the recent *Race Engine Technology Monitor* article on small-end design features (5) for more on small-end bushings.

Analysis

Increasingly, con rod makers are turning to analysis of one form or another in the design of con rods. Some use old-fashioned hand-calculations, albeit aided by the now-ubiquitous computer spreadsheet and a healthy amount of empirical data to produce safe con rod designs.

Others turn increasingly to finite-element analysis for optimisation of con rod designs. The recent advances in computing power, affordability and ease of use of many of the FEA codes mean that this technology is well within reach of many, although people should be beware of blindly believing the result without being able to verify it somehow with measured data. The old phrase "Rubbish In, Rubbish Out" is most apt when applied to computer analysis.

Those using FEA to a greater extent use it for prediction not only of maximum stresses, but fatigue behaviour, deformation, lubrication, wear, determination of natural frequencies of vibration among other things. Those with significant resources in this respect and expertise to use it effectively are able to produce the most highly optimised con rods for any given application. However, this all comes at a cost, as we can expect. Those looking to buy a heavily optimised con rod from such companies may have to pay for a design study beforehand, and then an expensive part price thereafter.

Benefits of Con Rod Development

Con rod development is driven largely by increases in engine speed, bearing technology and piston development. When a lighter piston is developed, the con rod sees lower stresses, and can correspondingly be made lighter, or we can use the same rod with a greater factor of safety. The lighter rod, if used, in conjunction with the lighter piston, means that the crankshaft is less highly stressed and can be made lighter by consequence. This all adds up to a much lower overall engine inertia which can improve acceleration and engine response. Some manufacturers say that there is a point beyond which a lightened crank-train is not a good idea, but others will always look for minimum mass and minimum inertia. It is clear that con rods can be developed for greater reliability, and this is a worthy aim.

A very relevant point which was explained is that improvement of the con rod is only really possible if the rod maker is given all of the relevant information and can see examples of the parts after use. In general, the manufacturers only see their parts again if they fail!

New Developments

Within the area of lubrication and bearings, there seems to be a push in some small quarters, albeit not across the whole industry, to dispense with the big end bearing and to run the crankshaft directly within the con rod. This appears to have had limited development, but we can confirm that some people have raced successfully without big-end bearing shells, not only in the motocross application (4) referenced earlier, but also in other applications.

The previously mentioned drive to run titanium con rods without a bush sees us with a coating supplier able to do this treatment, and one con rod manufacturer already admitting to running something which achieves the same end; it is surely only a matter of time before this gathers sufficient momentum to become almost universal as has happened with DLC-coated piston-pins.

There is a constant re-examination of con rod materials, and whilst race engine development is currently frozen in Formula One, the engine suppliers keep a keen eye on new developments and some have active materials development programmes with some looking specifically at con rod materials.

In terms of manufacturing technology, there are many exciting possibilities which are now open to the more adventurous manufacturers. Certainly making a pre-form from selectively laser-sintered materials is a possibility, and this may have seen some use already for experimental con ▶

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rods. The parts that I have recently seen (not con rods) in both titanium and other materials (6) have been of exceptional quality in terms of both surface finish and mechanical and physical properties compared to the same technology seen a few years previously.

Technologies which are mature in other arenas of engineering are slowly creeping into motorsport, and it is now perfectly possible to produce a hollow con rod (and other components) by a number of methods other than machining. Certainly one Formula One engine manufacturer has, in the past, experimented with one of these methods. One con rod manufacturer from the USA that we interviewed told how his hard-work in producing a hollow con rod shank resulted only in his labours being banned by the racing rule-makers.

Conclusion

We can clearly see that con rod manufacture and development has not reached a plateau, and with engine manufacturers, rod makers, materials engineers, developers of new manufacturing methods and coatings suppliers continually working hard, we have plenty of scope for development for the foreseeable future.

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