Ian Bamsey investigates piston ring technology for race engines

Rings of power

In addition to having two or three ring grooves cut above its skirt, a race engine piston sometimes has a larger number of very fine grooves cut around its top land area. These are not designed to accommodate rings. Often dubbed 'Anti Detonation Grooves', it is widely assumed that they exist to influence the path combustion gas finds as it spills over the top of the crown en route to the top ring. But ask ten experts how these grooves work and you will likely get ten different answers.

One answer is that an engineer at Cosworth pioneered top land grooving as a means of getting this area of the piston, which is critical to its running stability, to conform with the bore distortion that occurs at running temperature. Situated adjacent to the full heat of the combustion event, the top land area was made slightly oversize so that initially it would virtually seize at running temperature, whereupon in effect its melting aluminium would roll into the grooves as necessary to conform to the bore. Hey Presto: the piston had bedded itself in perfectly.

This ingenious engineer called the concept 'Scuff Banding'. We mention it here as indicative of the ultra-extreme conditions in which any race engine piston and its ring pack has to operate. It also emphasises the fact that it is the piston itself and not its rings that stabilises the operation of the piston assembly. The rings exist to seal, not to stabilise. More correctly, to act as a controller of combustion gas blow-by and of cylinder lubricant. Oil reaching the combustion chamber gets burned, increasing oil consumption, but in passing through the ring belt it provides vital upper cylinder lubrication for the piston assembly. The net effect in any race engine is a certain amount of oil consumption and by the same token a certain amount of blow-by. The key is to obtain the minimum oil consumption consequent upon adequate lubrication and with that the minimum blow-by.

To fully appreciate the technology of the piston and its ring pack it is necessary to appreciate that the race engine, while solid in the static state is in fact an elastic device (ie an elastic solid). The forces generated by its operation cause measurable deformation of its power components. A con rod stretches and compresses within the four strokes of the engine cycle. On top of this, the temperatures associated with engine operation influence not only bore shape but in particular the structure of the aluminium alloy piston. Under operational loading and temperature a piston crown will flex while similarly its skirt will deform. Such deformation of the piston is expected, so its design and that of the components with which it interacts must accommodate this.


U-Flex oil control ring (Photo: Total Seal)

RING OPERATION

The top ring has a vital role in helping reduce the thermal loading upon the piston crown. Operating under direct acting combustion pressure on every fourth stroke, it lives in an environment of excessive heat and somewhat indifferent lubrication. The oil control ring situated below lives in a slightly kinder environment as it glides over the cylinder wall oil film on each upward stroke while scraping excess oil on its way back down. All of the rings must operate at constantly varying speed from a momentarily stationary point as the piston is forced to change direction twice during each revolution of the crankshaft. On top of this the operation of the ring package affects the pressure distribution over the piston wall clearance area, which in turn affects lubrication at the interface of the distorted piston assembly and the distorted bore wall.

There must be some radial clearance between the inner face of a ring and adjacent groove wall (known as back clearance) to ensure that side forces acting on the piston are transferred to the cylinder wall via the bearing surfaces on the piston rather than through the rings. In fact, to permit lubrication between the ring and its groove there has to be some axial as well as radial clearance and this permits the ring to slowly rotate as the piston reciprocates, albeit not necessarily at a smooth rate of rotation. The various piston ring experts we consulted in preparation of this article told us that if a four-stroke race engine is running at 8000 rpm its rings are probably rotating at an average of something like 8 rpm within their respective groove. This ensures that the tangential force applied by a ring to the bore surface is consistent all around the circumference and it normally evens out ring wear.

To properly control blow-by, the top ring working face needs constantly to conform to the thermally and pressure distorted cylinder wall (normally bulging towards the top during combustion) while its lower side face needs constantly to conform to its groove in the thermo-mechanically distorted piston. Clearly a ring must run against the cylinder bore with sufficient pressure to attain full round contact yet no more than is adequate, so as to minimise running friction. Viscous drag comes into the picture, too, but this is not proportional to ring pressure and depends also upon the characteristics of the ring and the bore and the lubricant. The static pressure a ring applies to the cylinder wall is a function of its radial thickness, its axial height, it total free gap and the modulus of elasticity of its material.

In the dynamic situation the face profile will alter the pressure profile. Although there will be radial and axial clearance within the groove, this must not open a passage for blow-by. The forces to which the ring is subject must ensure that its lower side face is kept sealed against the ring groove on the power stroke (which means that piston groove surface finish is a key issue). In this situation there is scope for gas pressure to work from within the groove on the inner face of the ring – but hopefully not to leak underneath it. This gas pressure, which can be supplemented through lateral and vertical ports formed within the piston, adds to the static tangential force that the ring imparts to the wall.

The more we look in detail at the functions of a ring, the more complications we find and the greater becomes the difficulty of taking all of them into account so as to specify the ideal ring. Even equipped with the most sophisticated software, the required running data is so difficult to obtain, under normal circumstances at present there is little hope of genuinely modelling ring behaviour in the extreme environment of the race engine. It follows that ring development is in general at present an empirical process of trial and error. However, there are groups working to develop computer-based analysis techniques. The difficulty is high but doubtless in time realistic dynamic ring modelling will become feasible.

RING TENSION

In the past we have noted that in the context of a rev-limited IRL V8 the piston accounts for something like 40% of all friction and around 70% of the friction it generates is attributable to the ring pack. The total surface contact friction generated by a given ring running against the bore is the product of the relevant modified composite coefficient of friction and of the tangential force created by ring tension aided by gas pressure, sometimes enhanced by gas porting. While vertical gas ports are more direct acting, the operation of lateral ports can reduce ring flutter. Gas porting will potentially increase ring thrust at the cost of increased friction at the ring/bore interface. On the other hand it might permit a reduction of ring tension. In addition, one of our experts noted that through gas porting it is possible to alter the speed at which a ring rotates in its groove. However, gas porting is not without its dangers. Vertical gas ports can clog due to carbon build-up while even with lateral ports it is possible to have combustion occurring behind the ring. Moreover, the additional intricate piston machining necessary to form the gas ports adds complication and cost to piston manufacture.

Our experts reported that the static tangential force a top ring exerts on the bore wall nowadays is normally in the region of 2 N to 12 N. A highly turbocharged engine might require the extreme of 12 N whereas a typical NASCAR Cup (naturally aspirated, gasoline-fed, 5.87 litre, 9500 rpm) V8 figure is 4 N. Running anything less

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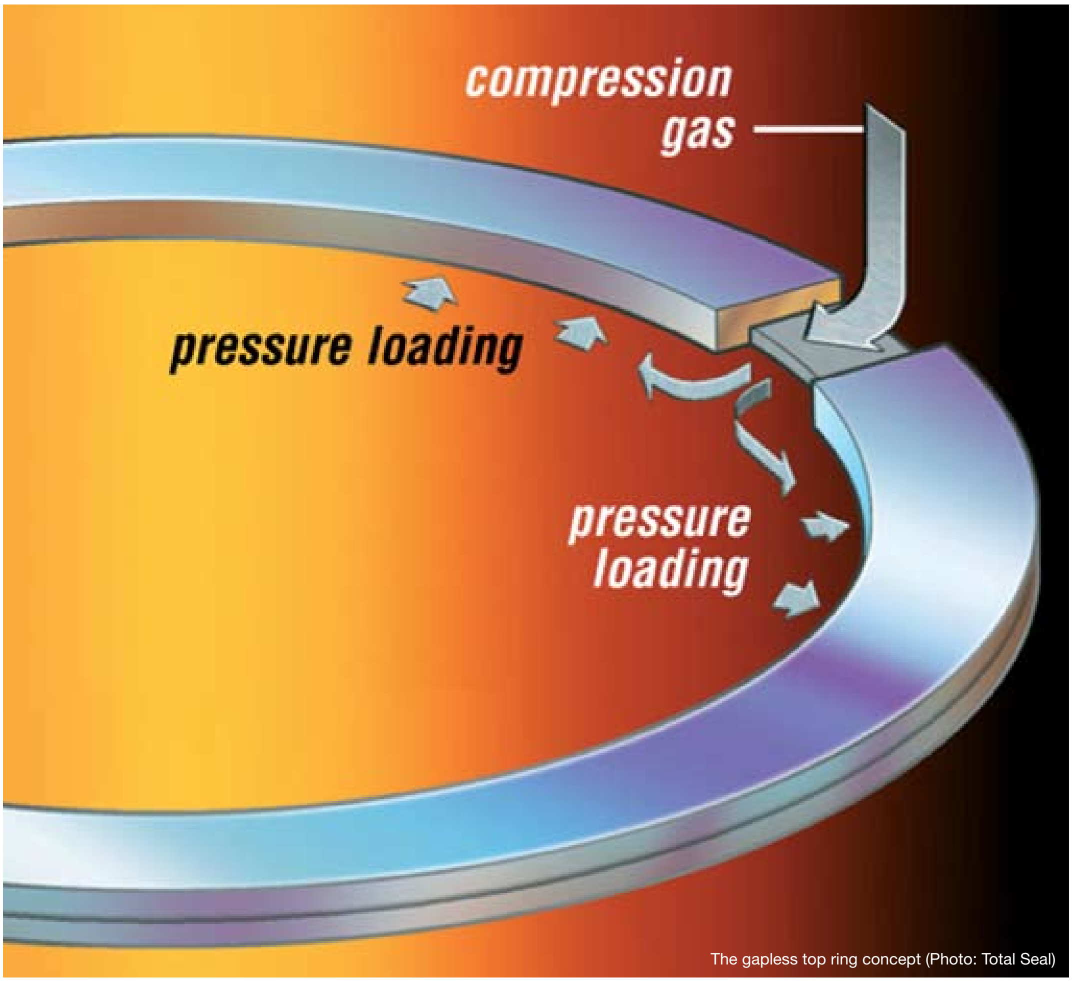

The gapless top ring concept (Photo: Total Seal) than that figure implies the use of gas porting, which means there is unlikely to be a reduction in terms of the effective tangential force. A figure of 4 N is characteristic of a high-end race engine – more mundane race engines are likely to see 7-10 N. To attain 6 N or less implies the optimisation of the bore surface finish and the lubrication. Ring dynamic performance and working surface finish also come into the design picture. One ring supplier recently introduced a new steel second ring using an alloy that better withstands the heat to which such a ring is subjected together with a titanium nitride working face coating. The upshot was a thinner, narrower alternative ring design with reduced tension.

TWO VERSUS THREE RINGS

On paper running with two rather than three rings offers a reduction in the total viscous drag created by the rings and a slight reduction in ring to bore friction. In addition it not only eliminates the mass of the second ring but also allows for the design of a shorter, lighter piston, with the pin closer to the crown, which further assists friction and minimises reciprocating weight. There might also be a reduction in the rod swing obliquity angle with consequent reduction of piston skirt friction. According to our experts there is no truth in the conventional wisdom that a two-ring piston will wear its rings quicker than a three-ring piston. In Formula One, recent increases in mandated engine mileage forced a focus as never before upon the deterioration in performance caused by blow-by. The cylinder bore shape, the piston shape and development of the ring pack were all important factors in trebling Formula One engine mileage. However, nobody resorted to a three-ring piston for these 19,000 rpm engines.

A three-ring piston does tend to make for lower oil consumption and on the face of it is the logical choice for 24 hour racing. Two ring pistons have been used successfully at Le Mans but that strategy calls for excellent ring operation, which in turn implies low cylinder bore distortion and the ability of the piston to provide a very stable ring platform. In general three-ring packages are more forgiving, inherently offering superior oil control, reduced blow-by and increased thermal transfer. They also tend to be less sensitive to crankcase windage, due to the fact that the second ring plays a significant role in oil control. Consequently a wet sump race engine is likely to benefit from a three-ring package. Also where cylinder pressures are unusually high the dependability of a three-ring configuration can far out-weigh the implicit performance loss.


Moly-filled top ring (Photo: Cross Manufacturing)

OIL CONTROL RINGS

Oil control rings can be one, two or three piece. However, the two piece ring, which consists of a C-shaped rail behind which is a spiral spring, is rarely employed in the race engine environment. Currently both one and three piece rings are in use in Formula One, Cup and other forms of racing.

In the case of the three-piece ring, these days normally the side rails are high carbon spring steel, sometimes nitrided, sometimes chrome plated, sometimes PVD coated. Traditionally the rails have been chrome-faced, an approach that has been known to scratch the cylinder wall. An alternative is a titanium nitride coating while metal-doped DLC has been successfully applied, with excellent frictional and wear advantages. The expander is often chrome nickel stainless steel and is not coated.

The alternative one-piece U-Flex acts as a gapless ring with its ends always in contact. Its sharp working edges make for excellent oil scraping while its flexibility helps it conform to cylinder bore and piston distortion. Its agility makes it more conformable than a conventional three-piece oil control ring and it does not lose that conformability as it wears, hence it retains its oil control property over time.

In general, using the U-Flex ring higher tangential loads can be run without an adverse effect on friction, while for a given level of friction it provides superior oil control. It can sometimes be used down to an axial height of 1.2 mm whereas three-piece oil control rings generally require a 2 mm axial height. In view of its flexibility the U-Flex ring is very challenging to coat, unlike the three-piece alternative with its stable upper and lower rails. Nevertheless, the plain steel surface of the U-Flex ring is understood to work well in conjunction with a nickel silicon carbide coated bore.

In the case of a methanol (or ethanol) fuelled engine, since the charge carries a relatively high proportion of fuel, a lot of it naturally threatens to get into the crankcase, where it will ruthlessly dilute the oil. A key challenge when running on alcohol is to stop fuel seeping past the pistons and consequently three ring solutions are common. In the case of the methanol-fuelled, lightly turbocharged, 2.65 litre Cosworth Indy Car V8, when it went from an open series contender to become the CART control engine the target was to minimise performance drop-off over 1200 rather than 400 miles. In view of this the switch was made from two to three rings, to minimise blow-by.

These days Cup engines are in effect rpm-capped by the Gear Rule and have to run one complete meeting – around 800 miles. The piston has to weigh at least 400 g bare and the combined effect of these restrictions has been to push Cup open (rather than restrictor plate) engines to three ring pistons. The enhanced blow-by and oil control provided by the second ring is beneficial for an engine that has to run a complete race meeting, on balance outweighing the lower friction obtainable using two rings. In fact the three-ring package might permit a reduction of oil control ring tension, helping to offset its disadvantage in terms of friction.

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TOP RING AND SECOND RINGS

For extreme temperature applications, beyond those normally experienced in the race engine environment a powder metallurgy alloy has been successfully applied to the manufacture of piston rings. Powder metals offer some interesting possibilities in the race engine environment but these days the hard-worked top rings are still generally made from cast iron or ductile iron or steel.

Traditionally fine grain cast iron rings have been favoured as affordable and compatible with both cast iron and nickel silicon carbide coated bores while offering good thermal conductivity, quick and accurate seating and good wear resistance. In the recent past, following introduction of the requirement to run two race meetings, the more forgiving cast iron top rings were used instead of steel in some Formula One engines to get the requisite blow-by control.

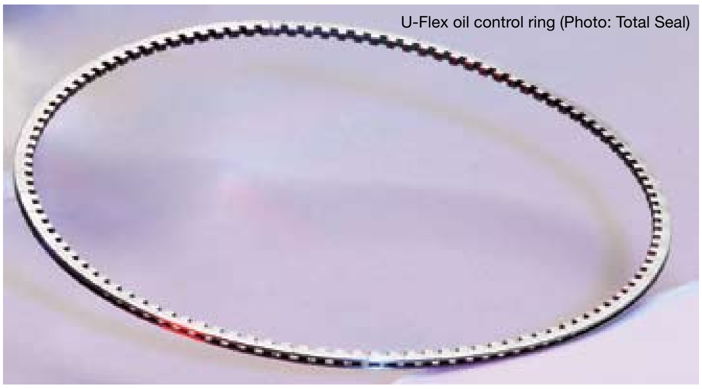
However, steel rings are inherently stronger and tougher and more heat and wear resistant than cast iron. Cast iron rings lose radial pressure more quickly with heat build up. Since they are less susceptible to fracture than cast iron rings, steel rings can be thinner and lighter for a given requirement. However, the inherently higher stiffness of a steel ring requires more force to displace it temporarily, to fit it over the piston, which in turn generates higher stress. The steel ring is also inherently less conformal for a given radial pressure.

However, arguably steel rings are more suited to advanced surface treatments and coatings. Generally these days (in the face of the crown temperature) top rings are steel while, (undertaking less severe duty) second rings are often cast iron. Nevertheless, the quicker bedding in of a cast iron ring can be significant. In one critical motorcycle race engine application, using steel top rings it took a number of hours of running to attain the maximum power potential. The engine builder switched to cast iron and achieved the same power level without wasting bedding-in time on the dyno.

The introduction of a nitrided stainless steel top ring has in one instance with which we are familiar been a successful approach taken to reduce ring radial thickness. The area over which gas pressure can act on the ring was thus reduced, helping lower friction while at the same time the switch from a carbon to a stainless steel meant that the conformability of the ring was increased, improving its sealing performance. However, while a nitrided stainless steel ring is fine for a plain iron bore it is considered by some of our experts too hard to run safely against a nickel silicon carbide bore surface. In fact, regardless of cylinder wall characteristics it is carbon steel that is the more common choice for today's top rings.

Cast iron as well as steel rings can be successfully nitrided, which helps the ring maintain tension in the face of extreme heat cycling. However, the nitriding process, whether gas or pulsed plasma can generate stress risers, leading to fracturing of the working face. The very best steel rings today may or may not be nitrided but always are precision machined from high quality steel and often have a PVD applied thin film surface coating that maintains the exact profile and all of the quality of the machined surface finish. A key to the performance of any ring, cast iron or steel is in the final machining. The best ring manufacturers today attain a surface finish in the range of 0.03-0.06 RA.

Ductile iron rings are centrifugally cast whereas cast iron rings are poured to shape in the foundry. In both instances the ring is finish machined. Steel rings are coiled from a flat extrusion then finish machined. Some manufacturers of steel rings have them CNC cam-coiled rather than mandrel wound in the normal manner, in which case there is no need for post heat treatment to hold ring tension.


U-Flex oil control ring (Photo: Total Seal)

THE RING GAP

A top ring could be designed so that when installed its ends touch. However, due to the complex thermal map of the piston/ring/cylinder system, together with differentials in thermal expansion, in practice there has to be some sort of gap at running temperature: it is critical that hot running doesn't lead to the ring ends butting into each other. Assuming the ring expands radially as appropriate for it to conform to the way normally the bore bulges within the hot zone, clearly the running gap will vary as the ring travels up and down the bore. In addition, the circumference (hence the diameter) of the ring increases with temperature, and the high temperature to which the top ring is exposed can cause the circumferential length of the ring to increase by 0.005" (0.125 mm) per inch (25.4 mm) of cylinder bore or more (depending upon the application – bore construction material is a major variable here – and upon the coefficient of expansion of the ring material).

The actual ring running gap is application specific – two different engines having the same cylinder bore size, running to the same rpm and producing the same per-cylinder power output do not necessarily present the same ring with the same operating conditions. Factors such as piston design and material, bore material and cylinder cooling provision all come into the picture. On top of that, in each case at any given stroke position the running gap is not a fixed figure since both operating temperature and component mechanical loading clearly vary with engine speed. So the true running gap is at best very hard to define. Our experts suggest that it would normally be found to be somewhere in the region of 0.25 mm (10 thou), plus or minus 0.05 mm – if it were feasible to measure it. Depending on the application, commonly used values for top-ring cold-installation end gap are 0.006 – 0.0075 inch (0.16 – 0.19 mm) per inch (25.4 mm) of bore.

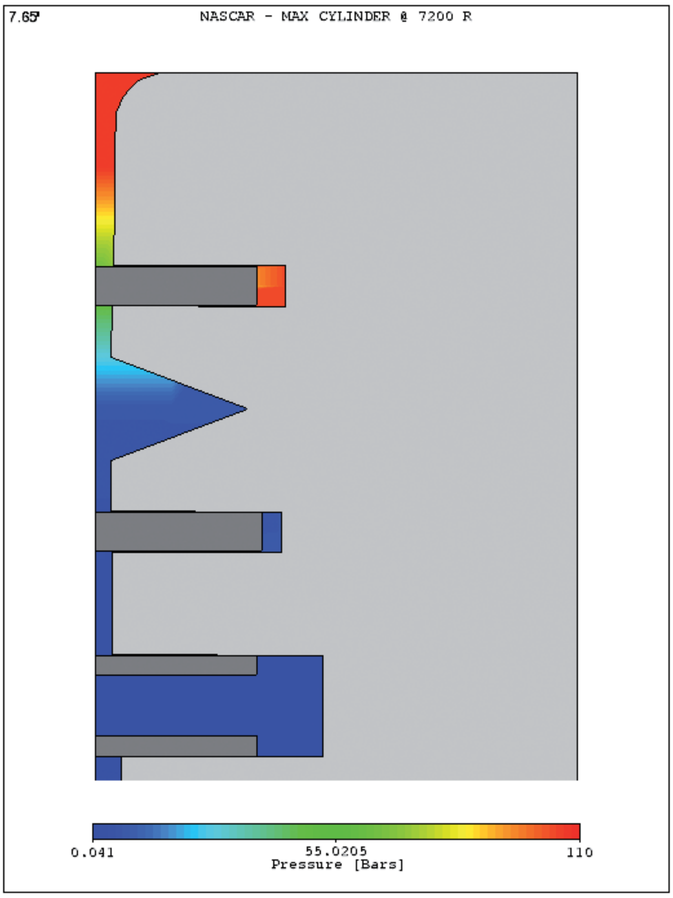
A ring gap doesn't have to be a straight section cut. The cut can be made at an angle or can even be stepped. However, none of the experts we consulted can see any reason for having anything other than a simple straight cut gap. Where the expert opinions differ is in the significance of the running gap.

There is a patented design of top ring that consists of primary ring plus a secondary rail that bridges the normal gap. The rail touches the cylinder bore, albeit having an undercut radius so to minimise the contact area and it has the effect of eliminating a running gap. This approach can represent a slight compromise in terms of ring size and mass and perhaps even dynamic behaviour but on the other hand it promises a reduction of blow-by. While not compromising the top ring's function as a thermal conduit, it enhances its other key function. Where our experts disagree is on the consequences of this additional sealing. In the absence of the normal rotating ring gap, the only way that oil can pass to lubricate the upper cylinder is through the cross hatching on the bore surface. This may or may not prove adequate, according to the specific engine application. It would appear that some engines (but by no means all) can benefit from reduced blow-by and reduced oil consumption using a gapless ring.

While the gapless ring is commonly seen as the top ring in a three-ring package, it is sometimes used instead as the second ring with then a conventional top ring. It is never used for both top and second rings since the pressure regime thus created promotes unwanted ring deflection. The use of any gapless ring impacts upon the pressure regime between piston and cylinder wall and proponents of gapless rings often claim increased intake suction.

To put the ring gap question into context, consider a Formula One engine having the maximum permitted 98 mm bore – this implies a top ring circumference of 307.87 mm, less any running gap. This 19,000 rpm engine will invariably have a gapped top ring and a representative running gap is 0.25 mm. So we can calculate that over the eight cylinders there is a total ring sealing length of 2460 mm and a total gap length of just 2 mm – a miniscule percentage (0.08%). This perhaps is more significant in terms of pressure differential above and below the top ring than in terms of the leakage of blow-by gas, which in any case occurs cyclically rather than as a constant flow.

But we didn't have consensus on this point across our various experts. Some buy into the gapless approach, others don't and the technology patent holder, as the current dominant Cup supplier, provides both gapped and gapless solutions according to engine builder choice.



JE Pistons study of piston and ring pressure loading

TOP RING AND SECOND RINGS (continued)

Occasionally one hears of cryogenic processing employed by ring manufacturers but this does not appear to be in widespread use. One supplier of 'cryo' claims that steel rings machine better after treatment as a consequence of a more uniform hardness distribution and typically will wear less and more evenly than untreated rings. None of our experts could recommend 'cryo' from personal experience but 'keep an open mind' was one comment.

It is not unknown for a ring's working face to be micro-pitted for oil retention. Beyond that coatings can be employed to potentially manipulate the behaviour of the oil film as well as reduce friction and wear and perhaps help combat microwelding. Clearly any such coating must withstand combustion heat and the friction and wear associated with the top ring's severe duty operation. In addition, since top rings are sometimes designed to twist in a controlled manner, there is not necessarily a particularly stable platform for the surface coating.

In some race engine applications the top ring is ductile or cast iron with a Molybdenum inlay. A channel is cut into the working face, into which the Moly is plasma sprayed then it is ground to the required barrel shape. The channel provides additional adherence area – the actual face working area is formed by the Moly, which provides a slippery surface that also retains oil well. This relatively inexpensive Moly-filled approach is sometimes applied to steel rings but it doesn't provide the durability and level of friction reduction that can be obtained using more recently developed, PVD applied thin film coatings. It consequently tends to be associated with less sophisticated race engines but some high-end engines still use the technology due to exceptional bore conformability and a high level of reliability.

PVD can be a suitably low temperature coating process and can embrace a wide range of materials. Often when the bore surface is nickel silicon carbide, the top ring is steel with a titanium nitride coating no more than 6 microns thick applied to the working face, to help minimise friction at the ring/bore interface and decrease wear. Given its minimal thickness the coating does not act as a thermal barrier. Consequently it can reduce friction at the ring/bore interface without harming the role of the ring as an escape route for piston heat.

One ring manufacturer offering titanium nitride reports that this extremely hard coating offers excellent performance throughout the life of the ring and can even lead to a situation in which post race dyno figures are higher than pre race ones. On the Vickers hardness scale titanium nitride measures 2300 HV yet it is known that some Cup teams have developed their own undisclosed alternative coatings, reaching as much as 3000 HV.

If there is a second ring often it is cast iron and uncoated. Sometimes, however, it is steel and uncoated or occasionally steel with a PVD applied titanium nitride or chromium nitride coating. The latter coating, which measures 1500 HV, has effectively replaced hard chrome in providing a more affordable alternative to titanium nitride. Chrome plating was once the industry standard and on the whole was a dependable solution. However in some instances it could be prone to flake. We know of one prominent engine builder using an iron liner who found a chrome plated second ring prone to flake and score the bore and who successfully switched to plain cast iron for this particular application.

Upper and lower side faces are sometimes coated to promote lubricity and with that rotation of the ring and to thereby minimise the danger of microwelding. One ring supplier forms tiny dimples

TOP RING AND SECOND RINGS (continued)

in these two faces, which are then filled with Moly to act as a dry lubricant. Also offered are PVD applied coatings, some as little as 1 micron thick, the specification of which tends to be undisclosed.

Some engine builders treat the groove itself, perhaps as an alternative to ring coating. However, the popular hard anodizing of the ring groove comes at the cost of its surface finish and the fatigue strength of the piston. These days, pistons are sometimes DLC coated, in which case the grooves are coated along with the skirt, faithfully maintaining the machined finish, not affecting its smoothness. Metal-doped DLC has been successfully applied (in one single PVD operation) to ring side and working faces providing excellent frictional and wear advantages. Pure DLC is a possible alternative that has not yet been as well proven in service.

While a DLC-coated working face does not lend itself to micro-pitting for oil retention, this is not the drawback it would otherwise be given the significant reduction of friction coefficient obtained when running DLC against a nickel silicon carbide bore coating or a plain cast iron bore. It is known that a high adhesion specification, metal-free multi-layer DLC that can be applied at low temperature has been successfully used for nitrided steel top rings in NASCAR and (German) DTM engine applications. The gain has been reduced friction with excellent wear characteristics against a regular bore surface. The DLC is applied to the side faces as well as the working face, again in one operation, to guard against microwelding. Only the inner face is uncoated – that is where the ring is supported in the coating chamber. Coating the ring surfaces thus reduces friction and wear to the extent that it is thought that a DLC coated ring set would be perfectly adequate to cover 5500 kilometres at Le Mans.

RING TWIST

Ring to bore contact is clearly influenced by ring flex, planned and unplanned. Planned (positive or negative) twist implies a manipulation of the dynamic behaviour of a ring, in the interests of enhanced conformability and sealing. Even Formula One top rings are sometimes designed to twist during operation in a carefully controlled manner. One supplier to many Cup teams reports that it supplies 0.7 mm high, stainless steel top rings with either positive or 'neutral' (ie zero) twist, according to engine builder choice.

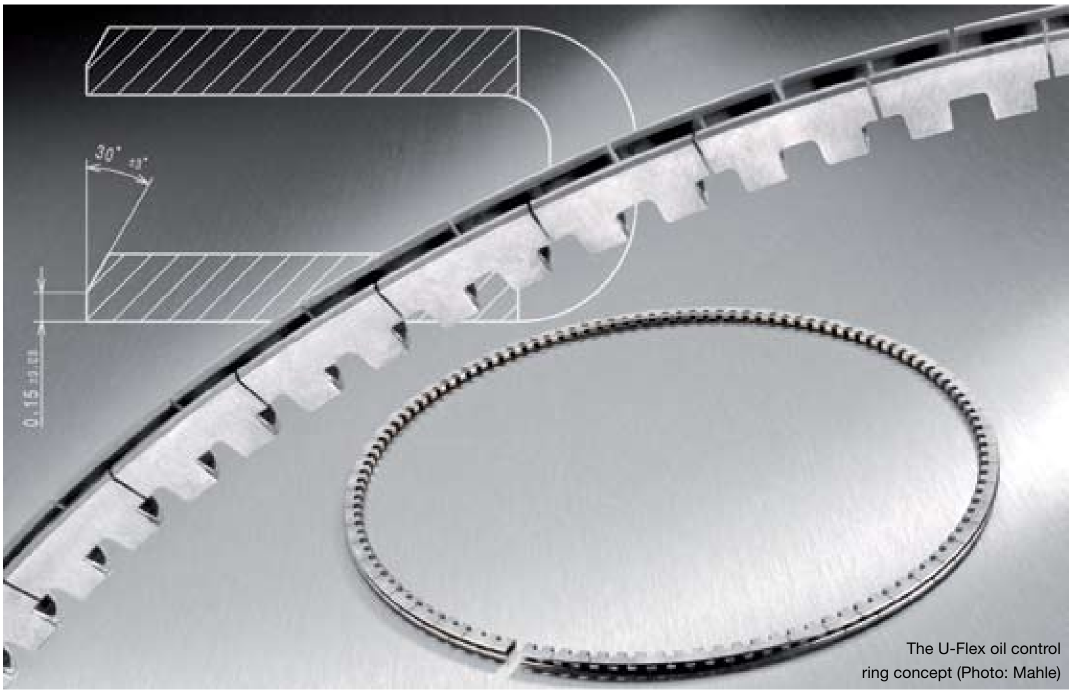
Exploiting a 'torsional' ring implies running greater axial clearance in the groove – in the case of a Cup ring perhaps 15-20 micron total clearance compared to 10 or less. In fact, in the absence of twist and given appropriate side face coating total top ring axial clearance can be as tight as 2.5 micron (one tenth of a thou), providing excellent control of the ring by the groove, helping it retain its design section and integrity in spite of the elasticity inherent in its material. According to our experts an average total axial clearance figure for a ring that doesn't exploit significant twist is 10 micron. Of course, reducing that down to 2.5 micron increases the danger of microwelding.

Another danger is that of ring flutter, which can lead to excessive blow-by. This unplanned flex is a function of ring mass, section and material. Flutter was a particular problem back in the late eighties/early nineties as Formula One designers tried to push the new 3.5 litre naturally aspirated engines beyond 14,000 rpm. To overcome it required painstaking ring and piston development, including reducing ring axial height down to 0.8 mm for the first time outside of motorcycle racing. The concept of a pressure relief groove was introduced, too. Reducing the radial thickness of a ring of given axial height can produce a ring that, thanks to being lighter is less prone to flutter as it is forced to change direction. On the other hand there is inherently a loss of radial force from the thinner ring. We know of instances where this has been countered by the introduction of gas porting.

RING GEOMETRY

Clearly rings must be as small and light as possible, not only to minimise friction and wear but also to help minimise the size and mass of the piston assembly. At the same time rings must be tough enough to withstand the thermal and mechanical stress incurred in operation. A ring requires adequate section to avoid unplanned flexing and potentially plastic deformation too. The lower the axial height of the top ring the better it will conform to the bore but at the cost of heat rejection due to the loss of working face area. When one considers that a significant amount of heat from the piston crown escapes through the top ring, one can appreciate the delicate balance that has to be struck between these various factors.

Interestingly, while in less severe applications the rings provide ▶



The U-Flex oil control ring concept (Photo: Mahle)

PISTON RING BASICS

Imagine a piston running without rings. Guided by its skirt and top land area it would still find its way up and down the bore but the clearance it needs to avoid seizure would permit excessive blow-by of combustion gas down into the crankcase, causing loss of power and dilution of the oil. At the same time an excessive amount of oil would get pumped up the cylinder wall, to be burned in the chamber (contributing to detonation sensitivity and the build-up of deposits) or to simply exit with the exhaust gas.

There are either two or three rings on a four-stroke, spark-ignition race engine piston: a **top ring** (otherwise known as the 'compression' ring) that primarily controls combustion gas blow-by, an **oil control ring** the function of which is self explanatory and an optional **second ring**, which assists the functioning of both of the other rings.

In addition to its primary control function, a piston ring assists in thermal transfer from the piston to the cylinder wall. The various rings operate in conjunction with the piston, the cylinder bore and the lubricant. Piston operational deformation and piston ring groove form and finish are all significant factors affecting ring operation as is deformation of the bore and the characteristics of its surface and the characteristics of the lubricating oil film.

The ring dimensions in the three axis are its diameter, which is influenced by its gap (free or installed), its (horizontal axis) **radial thickness** (sometimes referred to as its depth) and its (vertical axis) **axial height** (often but somewhat confusingly referred to as its width). Top and second rings are produced with (when seen in plan) a short radial section missing. Upon installation this **free gap** clearly can be increased temporarily, allowing the ring to be expanded so as to pass over the piston, en route to its groove. Having been squeezed to fit within the bore, leaving a certain **working gap** in trying to spring back to its original form the ring creates tangential tension right around its circumference. The radial pressure applied as the ring tries to regain its free gap keeps it in contact with the wall, assisted in the case of a top ring in particular by the pressure applied by the gas flow coming around the top of the piston down onto it.

Seen in section, each ring has an outer **working face**, a (horizontal) **upper side face**, a (horizontal) **lower side face** and an **inner face**. The working face of a top ring is often rounded – **barrel shaped** – but it might be **straight faced** with sharp edges or with rounded edges or **taper faced** with sharp edges or even L-shaped. The L-shape form is known as a **Dykes** ring and is rarely seen outside of drag race Fuel motors and some kart engines. In use in recent years in Formula One have been top rings either with a barrel shape or else rectangular with sharp edges – usually the barrel has been preferred over the rectangular shape.

A barrel face can be central or offset, which means that its centre point is not aligned with the horizontal central axis of the ring. Typically a second ring running face has a taper form. It is often of the **Napier** type having a notch in its lower surface, giving it a hooked form as befits its role as the second in line oil scraper.

Sometimes to ensure at all times face rather than sharp edge contact with the bore surface, a top or second ring is designed to **twist** up or down as it reciprocates (a barrel face is employed following the same logic).

A top or second ring that is rectangular in section aside from a chamfer on its upper inner edge is known as a **torsional ring** that has **positive twist**. On the intake stroke (ie when not heavily pressurised from above), groove clearance permitting the chamfer causes the ring to twist upwards (hence positive), as if trying to form a cone shape so that its lower outer edge meets the cylinder wall. This increases its oil scraping function. On the power stroke, the force of combustion pushes the ring back flat, maximising its gas sealing function. By the same token a top or second ring can have **negative twist** if its inner lower edge is chamfered instead.

The common **three-piece oil control ring** has flat upper and lower **'side rails'** that sandwich a spacer. The side rails have shallow running faces whereas the spacer, which does not contact the cylinder bore is deeper – for example, the rails might each be 0.5 mm deep, the spacer 1 mm. The spacer is sprung so as to tension the rails above and below it, increasing the pressure they apply to the bore. Moreover, this **'expander'** is designed so that oil trapped between the rails can flow through it and thence through drain holes in the piston back to the crankcase.

The alternative one-piece oil control ring is known as the **U-Flex**. It is made from spring steel, punched to obtain repetitive openings with additional cuts to one edge. The punched material is folded and pre-conformed into a U-shape to create a continuous formed profile. Like the three-piece ring it allows oil to flow through it and thence through drain holes in the piston back to the crankcase.

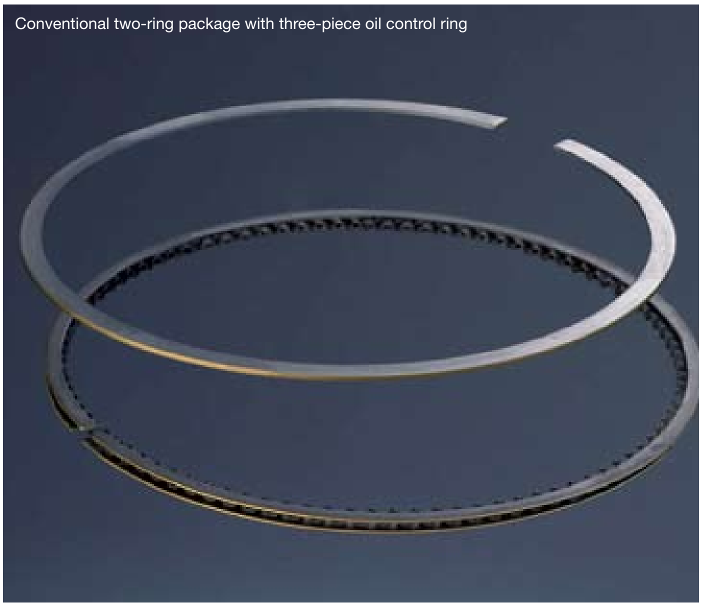
Between a piston's top ring groove and second ring groove there is sometimes an additional groove, which in section is triangular rather than square. Since blow-by inevitably leaks past the top ring this empty groove has the effect of reducing its pressure. Known as a **pressure seal groove** it reflects pressure waves, stopping the second ring receiving the full force of the leaking gas pressure. In turn this reduces the tendency to ring flutter and assists the sealing effect of the combustion gas pressure acting from above, which is trying to push the top ring down and out.

Although normally associated with the use of three rings, the pressure seal groove concept can be applied also to two-ring pistons. In a two-ring package the pressure waves such a groove creates can help scavenge oil leaking past the oil control ring. The groove also acts as a physical oil accumulator, collecting oil and encouraging it to flow back down. It also beneficially allows for the expansion of high-pressure gas, the increase in volume reducing its pressure.

Gas porting a piston is the technique of harnessing combustion gas pressure to apply additional thrust to a ring, helping seal it against the bore. It can take the form of vertical and/or lateral ports. **Vertical gas ports** are tiny drillings through the piston linking radially positioned gas entry holes in the crown surface to exits around the rear of the top ring groove. These ports allow combustion gas to pass down into the ring groove, where it pressurises the inner face of the ring. **Lateral gas ports** are semi-circular channels set into the top of the top ring groove that take gas coming around the top land to the rear of the groove, there to pressurise the ring's inner face.

Microwelding is a particular danger to the top ring, which transfers the majority of the heat from the piston crown to the cylinder wall. Promoted by the combination of high temperature and pressure and rapid movement that is characteristic of a race engine's cylinder, this phenomenon is not actually one of fusion since the steel of the ring cannot be welded to the aluminium of the piston but is in fact micro-cracking followed by welding of ejected material, leading to galling as the ring is pushed up and down and rotates. It occurs when the ring cannot transfer heat fast enough, so heat builds up and in this case there will eventually be some transfer of material between the rotating ring and its groove, stopping the ring conforming properly to the bore and ultimately leading to ring seizure.

Thus, microwelding is a combination of surfaces and possibly coatings and also lubricant not working together under the given operational conditions. It is often the result of hot combustion gasses getting behind the ring and overheating it. It is worth noting that in general a methanol-fuelled engine runs cooler than a gasoline-fuelled one, in view of which there is less of a tendency to microwelding. For reasons described elsewhere in this article methanol engines tend to run three rings, which increases the heat path from piston to bore, further reducing the danger of microwelding. In general terms, microwelding can be avoided by a high quality of ring groove finish, high quality of ring finish in terms of flatness and smoothness, with perhaps appropriate side face coating of the ring, good lubrication and a homogenous temperature distribution around the grooves.


Conventional two-ring package with three-piece oil control ring

the primary path for heat to escape from the piston, these days race engines often employ sophisticated oil jet cooling to the piston underside. Typically these days a very significant proportion of heat removal is via oil spray cooling rather than ring cooling.

In recent years there has been a trend to make the top ring shorter and to move it up closer to the piston crown face. A ring of reduced axial height requires less material around it, assisting the design of a lighter piston. Interestingly, though, in at least once instance it has been found that a steel alloy which provides enhanced thermal conductivity yet requires additional section thickness to avoid elastic deformation is overall of benefit, since it causes the crown to run cooler and thereby can the crown be made thinner.

In general the use of a second ring does not tend to imply a reduction in the axial height of the top ring, although sometimes the second ring is found to be slightly taller than the top ring – the respective sizes might be 1.2 mm and 1 mm. More commonly today, in high end racing, ring axial heights are 1 mm or less for both top and second rings. Alone or in tandem, top ring axial height is largely influenced by cylinder pressure and today in two-ring Formula One and in three-ring Cup applications typical dimensions are 0.8 – 0.6 mm. In fact 0.6 mm is about the shortest feasible ring axial height, most commonly found in smaller displacement motorcycle race engine cylinders. By contrast the racing turbodiesel engine top ring is typically more than 2.0 mm high since it has to face the significantly higher cylinder pressure associated with compression ignition. The highest top and second rings for extreme spark ignition applications tend to be 1.5 mm.

In the past there was a European and an American formula that each defined appropriate ring radial thickness according to cylinder bore size. The European ratio was bore diameter/26 whereas the American ratio was /22. In other words the American formula looked for a greater radial thickness, for greater radial pressure at the expense of increased friction. The Cup V8 has a bore size of 106.3 mm and consequently would have a ring radial thickness of 4 mm under the European formula and 4.8 mm under the American one. Modern design techniques allow for individual tailoring of ring axial height and radial thickness. On top of that materials and coatings have improved vastly: back in the days when those formulae were current, the rings would have been more than 1 mm high. Nowadays, as a guide, a steel Cup ring that has the extreme axial height of just 0.6 mm can be expected to have a radial thickness of 2.5 – 2.8 mm whereas a more common 0.7 or 0.8 mm ring will typically be 3.0 – 3.5 mm thick. It is worth noting that the change in stiffness consequent upon the trend to move from cast iron to steel for the top ring has been a key factor in maintaining the required radial pressure from a ring of reduced dimension.

The oil control ring, which can be a three-piece or a one-piece ring according to engine builder choice typically is 2.0 mm high with a radial thickness of 2.5 mm or thereabouts, although smaller sizes may be exploited. An 0.8 mm top ring with a radial thickness in the region of 3 mm will weigh approximately 6 g. These days a three-ring Cup piston has a total ring weight of no more than 20 g and current development is edging towards 15 g.

THE RING ENVIRONMENT

One factor influencing ring performance is the type of fuel burned, while it is worth considering that the introduction of an efficient intake air filter can reduce bore and ring wear. Also it is worth noting that the lubricant is common throughout a given engine and has to apply an adequate solution to a wide range of surface contacts, which vary widely in parameters. In satisfying this, optimal lubricant performance for the piston/ring/bore system throughout the engine operating range is not truly possible.

At mid-stroke a piston and its rings will have hydrodynamic lubrication, changing to mixed lubrication as the piston slows towards top and bottom dead centre, where the boundary lubrication condition is experienced. In a high-output compression-ignition engine, the combination of boundary lubrication and the extreme cylinder pressures causes wear of the top ring and the cylinder bore around TDC to be an especially challenging problem. One cylinder bore specialist offers 'Engineered Surface Technology', whereby different surface conditions are applied to specific areas of the bore surface to optimise running conditions in recognition of these differences. In effect the bore surface is locally modified via etching so as to reduce oil drag at the ring/bore interface.

At the same time controlling the effect of piston distortion is a key to optimising the operation of the ring pack. A ring groove base might not be cut perpendicular relative to the piston axis. Sometimes the top ring groove will be machined with a slight upward tilt, with the intention that it should run flat under normal operating conditions. In Cup racing there is that mandatory minimum (bare) piston weight of 400 g and this has put great emphasis upon piston mass balancing. It has also led to careful attention to material distribution with a view to providing enhanced support for the ring belt. In fact, such ring platform stability is one advantage of a steel piston, a technology so far only introduced for racing turbodiesel engines. Clearly, by using steel rather than aluminium pistons, the stability of the piston/ring system will inherently be superior and at the same time the piston will match steel rings in terms of thermal expansion. Consequently there is a

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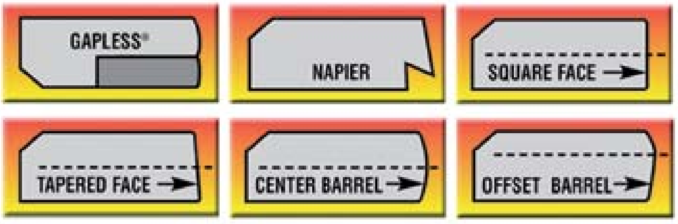

Types of top and second ring

potential improvement in oil and blow-by control attributable simply to this change of piston material. For other reasons, steel has not yet been used as a piston material for spark-ignition race engines.

In terms of the interaction between a piston and its rings, there are of course both mechanical and thermal considerations. There is a critical relationship between piston heat distribution and the stability of the ring belt, where thermal behaviour is influenced both by piston geometry and by piston cooling, which might be augmented by an oil spray to the underside. It is worth noting that ring grooves can be subject to local hot spots, typically where stiffening elements are attached to the ring platform. Such hot spots lead to local ring groove deformations.

Piston ring groove surfaces are often treated or coated to ensure adequate rotation of the ring and help minimise wear, with reduced danger of microwelding. Sometimes a phosphate dip process is used to deposit phosphate in each groove for its dry film lubricant properties. Some race engine piston manufacturers offer an electroless nickel coating instead. This is a chemical process with, as the name suggests, no electric current involved, which deposits a layer of nickel-phosphorous alloy onto the surfaces of the groove. Appropriately, it does not form a thermal barrier and it does help guard against the build up of deposits. But much more often grooves are hard anodized rather than coated.

Hard anodizing is an electrolytic passivation process used to increase the thickness of the natural oxide layer on the surface of aluminium alloys, without causing any distortion to the part. This durable coating, which can be harder than case-hardened steel, is protective of the ring groove. However, the use of the process on aluminium, especially in the areas of sharp inside corners, will decrease the fatigue life of the base material. Moreover, while protecting the ring groove against wear, hard anodising increases its surface roughness so it leaves a less than perfect surface against which the lower side face of the ring must seal, hence on the face of it increasing the propensity to the very microwelding it seeks to combat. Microwelding has been shown to be micro-cracking followed by welding of ejected material. Anodising increases hardness thereby minimising cracking. As anodising is in fact a complex alumina it does not readily weld anyway.

Turbodiesel ring set (Photo: Mahle)

PISTON RING SUPPLIERS

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Mahle	+49 711 5010
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NPR	
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Riken	+81 3 3230 3911
www.riken.co.jp	
Teikoku Piston Ring Co., Ltd	+81 3 5293 2811
www.tpr.co.jp	
SWEDEN	
Daros Piston Rings AB	+46 31 338 4000
www.daros.se	
TURKEY	
Samsun Segman Sanayi, Inc (Power Seal)	+90 362 2669187
www.samsunsegman.com	
UK	
Bradford Piston & Piston Ring Company	+44 161 736 5211
www.bradfordpistonrings.co.uk	
CORDS Duaflex	+44 1685 353240
www.cordsduaflex.com	
Cross Manufacturing Company (1938) Limited	+44 1225 837000
www.crossmanufacturing.com	
USA	
Federal Mogul	
www.federalmogul.com	
Grover Corporation	+1 414 384 9472
www.grovercorp.com	
Hastings Manufacturing Company	+1 269 945 2491
www.hastingsmfg.com	
Total Seal	+1 623 587 7400
www.totalseal.com	

Plasma electrolytic oxidation is a process that can be used to transform the surface of aluminium alloy into a hard, dense ceramic with high wear resistance. This can replace the hard anodizing of ring grooves, potentially offering greater wear resistance while the very thin layer required in this application should improve the heat flow out of the piston through the top ring, compared to an anodized groove. The reduction in fatigue strength due to the high hardness is also an issue. This process is not commonly exploited, nevertheless.

One piston supplier is experimenting with a new manufacturing technique that exploits compressive stress. Each groove is made undersize and then a rolling process is used to force it to the required size. The piston is spun on its axis and at the same time a spinning wheel pushes its way around the circumference of the groove, maintaining the established radial thickness while forcing for example a groove machined to 0.95 mm out to the required 1.0 mm axial height. The plastic deformation thus promoted produces a harder groove surface. ■