Crank

Years ago, one especially unsuitable engine I attempted to develop for racing broke crankshafts in a little less than an hour of track time. The fracture always occurred in the same web joining a main bearing and connecting-rod journal. After the second failure, I began to suspect that something more than hard luck was involved.

Examination showed the breaks had started in the drilled oil-way leading from the number-one main bearing out to the adjacent rod journal. The oilway passed near the crank web's surface at one point and had scored walls from having been drilled too fast and forcefully. Scored grooves inside the oilway were starting cracks, one of which would then spread until the web fractured through.

When drilling the roughness out of the oilway yielded ambiguous results, I began thinking in terms of designing and making a better crankshaft. "Why not?" I thought. I had a drawing board, paper and access to a machine shop with lathes big enough to swing billets for cranks far larger than the one I envisioned. What I lacked was knowledge, which I set about acquiring with my usual disorganized flakiness. And the first thing I learned is that there's a lot to know.

If you're willing to spend a lot of time dodging smoking-hot metal chips in front of a lathe, or pay someone else to do it, making a crank is relatively simple. The less you know the simpler it is. If you don't know anything, you can start with a billet of easy-to-machine, low-carbon steel. Once you *do* know something, you'll carve your crank from SAE 4340 or 5140 steel, which is tougher and doesn't cut as easily. The latter, 5140, can be hardened by baking it in cyanide salts and quenching it in

By Gordon Jennings

Illustration by Doug Fraser

shafts

Turning up and down into 'round and 'round.

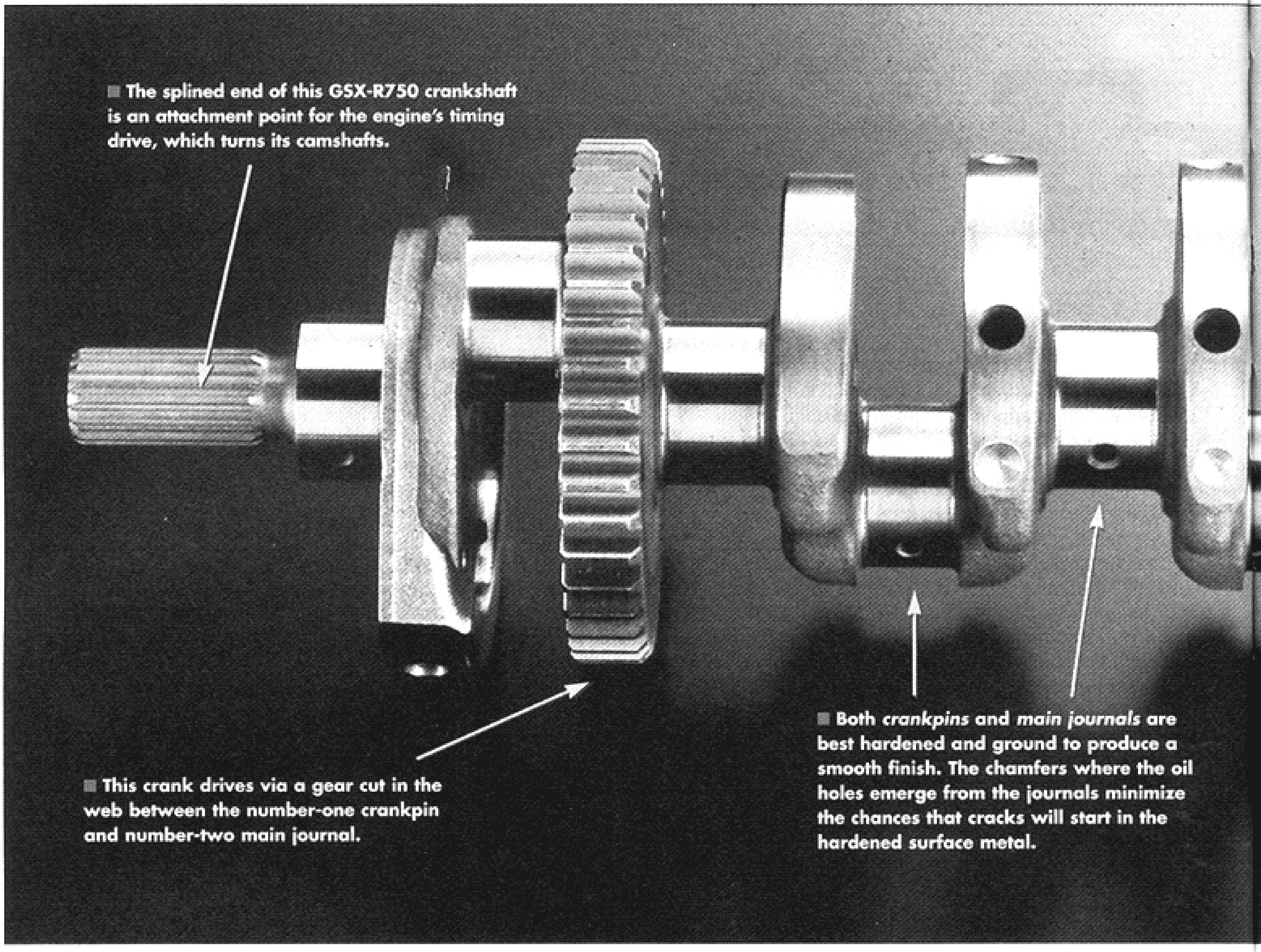
oil; not exactly a process you want to try in your kitchen, but one that works. Hardened journals will shrug off just about anything that might happen to them in a running engine.

Cranks for series-produced engines are either cast or forged. Cast iron is a little weak under bending loads, but it self-damps vibration and its journals resist scoring. Stronger cast steel is used for both cranks and connecting rods, and is satisfactory for all but high-output engines. Motorcycles mostly get forged cranks, usually without the twisting inflicted on those made for automotive V-type engines. Such cranks are forged flat, then twisted to move their crankpins into position.

Motorcycle cranks usually have more—and larger—counterweights than their car-engine cousins, because few bikes (except BMW and Moto Guzzi twins) have flywheels. Old Triumph twins and their like had substantial flywheels in their between-cylinders space instead of a center main bearing. The V-twin layout invites the designer to provide a pair of large flywheels. But the ubiquitous in-line four is an array of small diameter flywheels joined together with main bearing journals and crankpins.

Without exception, today's in-line motorcycle engines have main bearings on both sides of each cylinder. Fours, for example, support their cranks in five main bearings—a big change from the old days. Most of the early in-line fours had only two main bearings, one at each end of the crank. The inadequacy of this arrangement became clear when it was discovered that the unsupported crank flexed enough to let the pistons in cylinders two and three strike the underside of the cylinder head.

We have learned since those early days that crankcases must provide the support for cranks, and not the other way around. I saw awesome evidence of this in Yamaha's TZ350



■ The splined end of this GSX-R750 crankshaft is an attachment point for the engine's timing drive, which turns its camshafts.

■ This crank drives via a gear cut in the web between the number-one crankpin and number-two main journal.

■ Both *crankpins* and *main journals* are best hardened and ground to produce a smooth finish. The chamfers where the oil holes emerge from the journals minimize the chances that cracks will start in the hardened surface metal.

engine, which had a stock RD350 crankcase topped by a water-cooled racing cylinder block. At the TZ's level of output, the RD crankcase flexing was such that the crank's outer main bearing races scrubbed metal out of the iron bearing housing inserts.

The most heavily loaded bearing in an in-line four is the one between cylinders two and three. After its 1.5-liter V-16 GP car engine bombed (an especially apt simile), BRM went to an imaginative in-line four. BRM's engine guy, Peter Berthon, minimized the effects of crankshaft twisting on valve timing by locating the timing drive next to the flywheel. And—get this—he solved the problem of middle main bearing failures by eliminating that bearing altogether, leaving it to the remaining four to carry the loads.

Roller bearings are in theory anti-friction, but they do create drag within themselves and elsewhere.

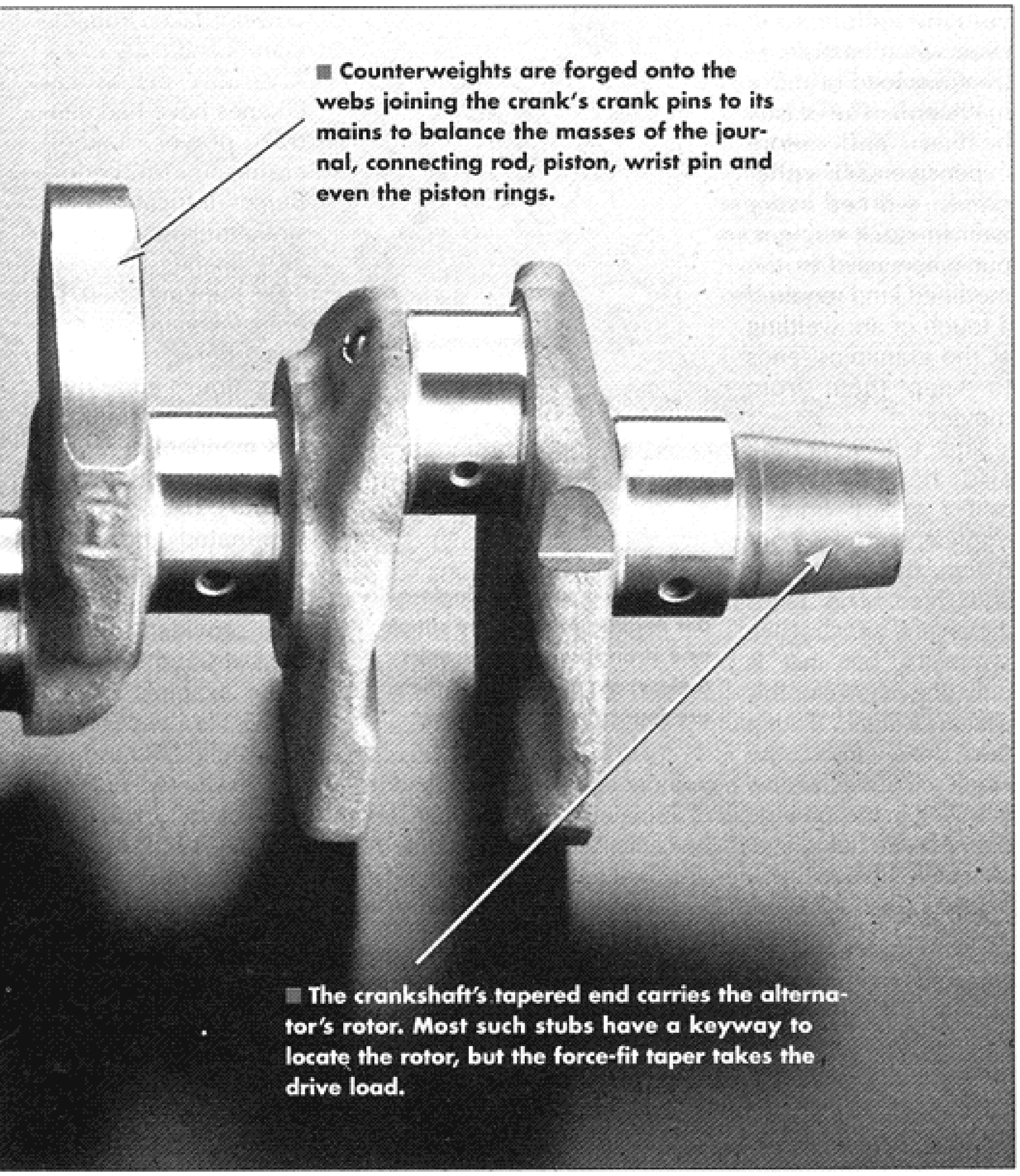
Modern motorcycles' bore/stroke ratios, mostly in the 0.7:1 to 0.8:1 range, make for strong crankshafts. Crankpins generally have diameters between 60 and 75 percent of cylinder bore, and a length slightly more than half their diameter. An in-line four with 75mm bores would have a crankpin diameter of, say, 50mm, and a width of 28mm. Even in an engine with bores set fairly close together, the main bearing journals will fit under the width required for two cylinder liners, supporting walls in the block and water jacketing. So the webs connecting the main journals and the crankpin can have a width of 22mm, a generous plenty.

If the above hypothetical engine's displacement is 1000cc, then its stroke would be 56.5mm, which puts an offset of 56.5/2 (which equals 28.25mm) between the main bearing and connecting rod journals. If both journals have a diameter of 50mm they will overlap 21.75mm, meaning the crank would hang together fairly well without needing any webs between journals.

I was for a time greatly taken by rolling-element anti-friction bearings on cranks. When you don't know anything (everyone's starting condition—mine for longer than is seemly), rolling looks much better than sliding. And, in fact, if we could be sure rollers would always roll, and cranks always crank and nothing else, bearing choice would indeed be weighted in favor of rollers. But, these conditions are not always met.

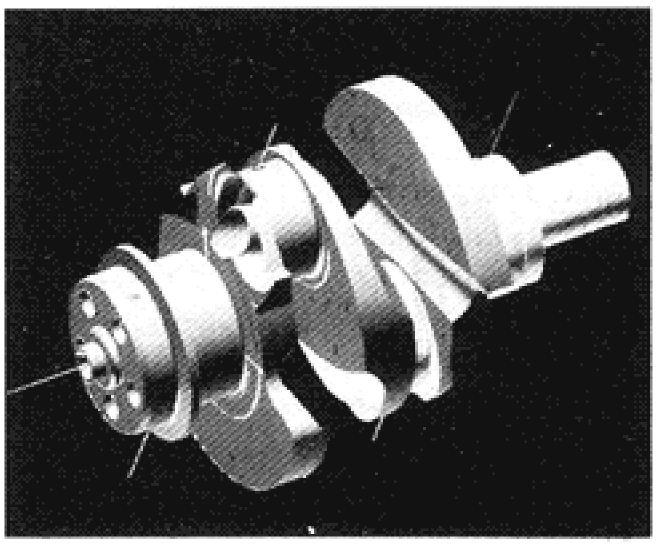
Roller bearings are in theory anti-friction, but they do create drag within themselves and elsewhere. These bearings' line contact creates extremely high unit-area loads, causing the rollers to push a slight rise ahead of them in their loaded race as they proceed around. Further, because the race distorts unevenly, more under the center of the load than at the sides, some scrubbing occurs in addition to the expected rolling.

Under crankshaft conditions, roller and plain insert-type bearings produce essen-

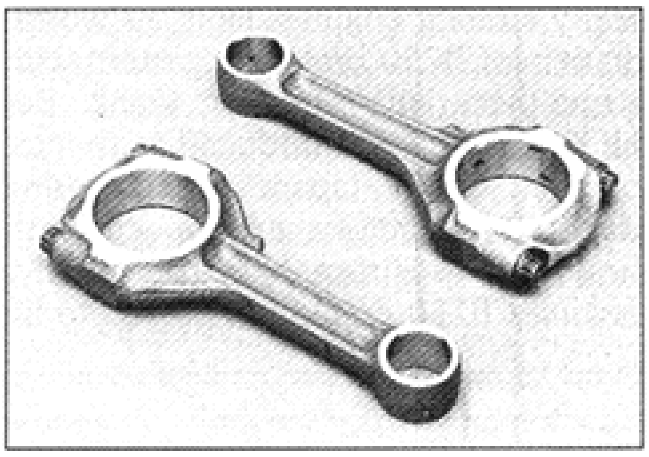


■ Counterweights are forged onto the webs joining the crank's crank pins to its mains to balance the masses of the journal, connecting rod, piston, wrist pin and even the piston rings.

■ The crankshaft's tapered end carries the alternator's rotor. Most such stubs have a keyway to locate the rotor, but the force-fit taper takes the drive load.



■ BMW's boxer engines have all had two main bearing crankshafts similar to this one. The width of the "flying web" between the two crankpins has to be minimized in the interest of preventing a too-large, unbalancing offset between the opposed cylinders.



■ These Honda VTR1000 connecting rods have their caps secured without the use of nuts on the top ends of the rod bolts, eliminating the inevitable weakening effects of the clearance notches otherwise required.

tially identical levels of drag. A slight advantage is possible with short, large-diameter rollers. This specification is most easily met on cranks for single-cylinder and V-twin engines, where in fact roller bearings are most commonly found.

Connecting-rod swing can cause roller bearings to skid. For about 100 degrees both sides of bottom center, the rod's swing makes it turn with the crank pin, slowing the rollers' rotation on their own axes. But on the approach to top center, rod swing produces contra-rotation, increasing the rate of roller rotation. So, we have rollers cyclically accelerating and slowing as the crank turns. The bearing cage must do the same, and this is the arrangement's Achilles Heel: At high engine speeds, bearing cage inertia can make the rollers skid, producing rapid bearing failure.

Bearing drag rises sharply with journal diameter, which is indirectly another reason why singles and many V-twins have roller cranks.

Roller-bearing cages were once commonly made of bronze, but the weight of that alloy became a fatal cause of roller skidding. Aluminum replaced bronze, and in many engines steel has replaced aluminum. Steel is, of course, a fairly heavy metal, but its strength is such that a trimmed-down lattice is enough to guide the rollers. Moreover, steel's hot-strength is much better than that of aluminum. Beryllium, which is 40 percent lighter than aluminum, would be the perfect metal for bearing races but for being hard to machine and toxic for machinists. The hot-strength of titanium is better than steel, it's almost as strong at all temperatures, and it's half as heavy—but it's expensive.

In all cases, roller-bearing races have to be designed and made without sharp corners anywhere. Cracks often start in the ends of the roller-guide slots, where corner radii are too abrupt. Also, experience has shown that roller-bearing cages of whatever metal, including aluminum, need antiscuff coatings. Racing engines' cages—now often made of titanium—are plated with tin or silver, the latter being more effective. The same platings have been used on steel cages, but phosphate treatment is less expensive and works nearly as well.

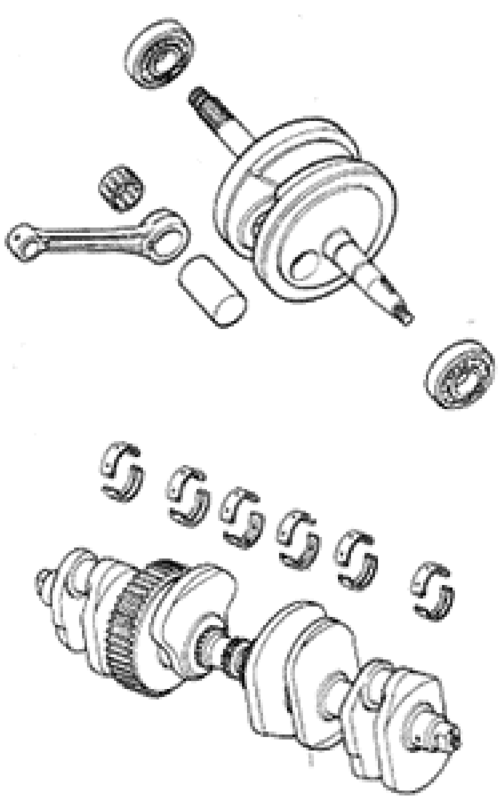
Bearing drag rises sharply with journal diameter, which is indirectly another reason why singles and many V-twins have roller cranks. Engines with two or more cylinders in a row have an indirect torque path, with power pulses most remote from the crank's output end passing across one or more other crankpins to get there. Power-pulse and inertia hammering make cranks vibrate in torsion, and the need to keep this twisting from breaking the shaft imposes the lower limit for journal diameter.

A crank with journals either machined or cast to have hollow centers is less likely to break from twisting than the solid kind. Such cranks twist more but behave like tubular torsion bars in having no conflict between tension on the outer surfaces and compression at the center. Similarly, cranks can be strengthened by trimming away metal adjacent to stress points to keep loads from focusing there.

In engines with pressed-together cranks, crankpin diameter provides the torque capacity required to keep the crank from being twisted out of alignment. You get a fixed clamping force from the interference fit between crankpin and crank web, one determined by the metal's yield point, which is about the same for all steels used in making pressed-together cranks. Resistance to twisting then becomes a function of contact area between the crankpin and the crank-web hole into which it is pressed.

At one time, most of Japan's motorcycle manufacturers used roller cranks in nearly all their engines. Honda's world-changing CB750 broke the pattern with a one-piece, plain-bearing crank. But the Kawasaki Z-1 introduced soon after followed earlier Japanese engineering practice. Ex-factory experience with these engines is revealing: The spindly-looking CB750 crankshaft proved to be virtually failureproof, even when hammered by a big load of nitromethanol. The vastly heavier and more expensive Z-1 roller crank worked very well in stock engines, but when used in the modified kind required a touch of arc welding at the crankpins' ends to keep them from moving.

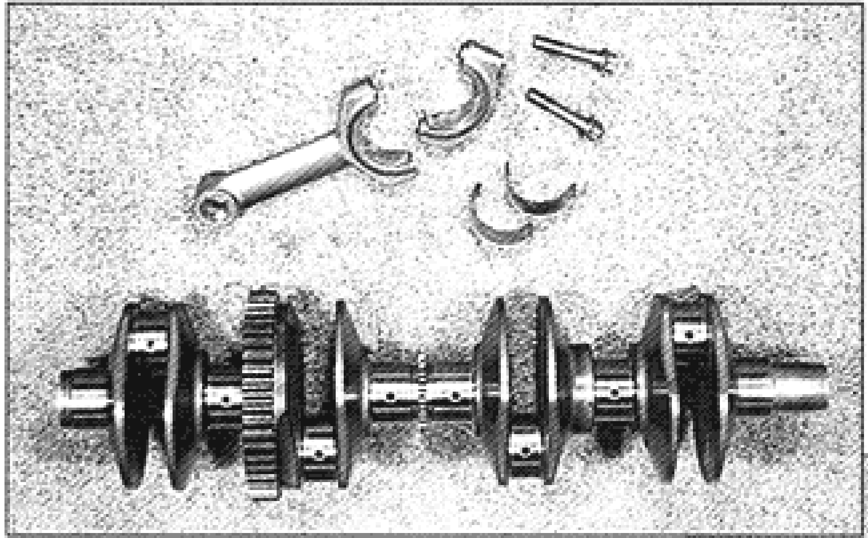
The CB750 crank also had a central power takeoff from a duplex sprocket between cylinders two and three. This lends the engine an attractive symmetry, but that is only one reason for this design feature. Taking the drive from the crank's middle means two short cranks vibrating in torsion instead of a single long one. All else being equal, the center-takeoff crank vibrates at twice the frequency but half the amplitude than when the power is taken from the crank's end.

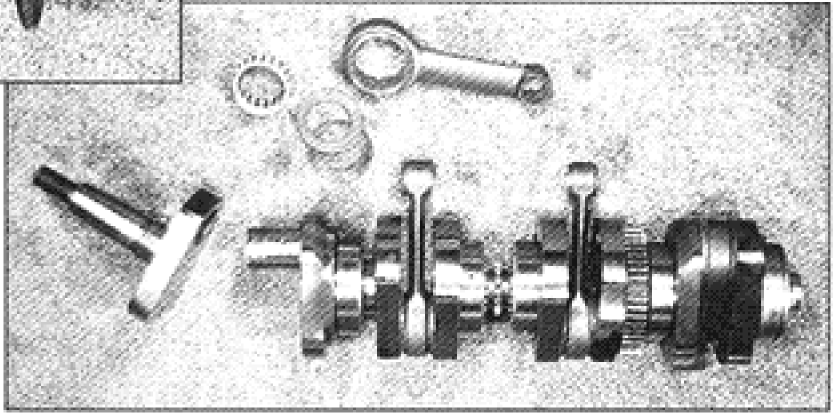


■ **Built-up cranks for single-cylinder engines (above) are simple and strong; one-piece cranks (below) are better when there are four cylinders in a row.**

Various racing car engines have had central power takeoff cranks. Mercedes-Benz's intricate M196 straight-eight engine, a '50s manifestation of '30s thinking, had its drive taken from a spur gear between cylinders four and five. Dividing the crank in this manner, into what effectively was a pair of fours, back-to-back, eliminated the need for the torsional vibration dampers invariably provided on in-line sixes and V-8s.

The example of the M196 is especially interesting because its multipiece roller crank was not pressed together. It was made by Hirth, with parting lines straight across each bearing journal. The matching faces of each journal half had precision-ground radial





■ Today's in-line fours all have plain-bearing cranks like the Falicon-modified unit at left. Kawasaki's early fours had caged roller-type bearings that required that their cranks be a pressed-together collection of numerous bits and pieces.

splines, and the faces were pulled together by Hirth's famous (in engineering circles) differential threaded couplings. These couplings had two diameters, both threaded but with the smaller end having slightly coarser threads.

The Hirth crank was assembled by inserting the couplings through the threaded center of each journal half and screwing them into place. Threads on both sides of the join engaged at the same time, but the coupling's coarser-threaded forward end gained on the fine-threaded rear as it turned. When screwed into place, the coupling's differential threading pulls the journal halves forcefully together.

Torsional vibration dampers of the type commonly seen on big V-8s use rubber bonded between a hub, splined or keyed to the crank's nose, and a small flywheel. When the crank begins to vibrate in torsion, the vibration is damped by the rubber's hysteresis, or internal friction. Others use friction disks, either dry or in an oil bath, and still others use the viscous shear of oil alone to damp twisting vibration.

Motorcycle engines typically have not had "harmonic" crank dampers, and haven't needed them. The same is not true of automotive engines, especially in-line sixes. The old long-stroke Jaguar engine in racing form delivered enough power to severely twist its seven-main-bearing crank. Drivers who ignored the redline risked seeing broken shards of crank flying out the bottoms and sides of their cars.

One common feature of Japan's roller cranks that few others have dared attempt is the way the crankpin is made integral with one flywheel. The advantage here is that it makes the crank more rigid in torsion. Cranks of any sort have to be made with great precision. Crankpins, for example, should be parallel with a crank's main shafts to within a micron over a distance of 100 millimeters.

Whatever the respective merits of the two kinds of bearings, the present trend

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toward big cylinder bores, short strokes and higher crank speeds makes rollers unattractive. A plain bearing crank's stroke can be shortened until it's zero without creating mechanical difficulties. But, the multipiece cranks required for roller bearings become expensively complex when the stroke is reduced to the point that you have overlap between the crankpin and main bearing journal diameters.

It is possible to use roller bearings on a one-piece crank, as in numerous two-stroke engines. However, this requires either using two-piece roller cages or no cage at all, expedients appropriate only when scanty oil-mist lubrication (as in two-strokes) make rollers a necessity. Yes, Moto Guzzi and others have used split-cage/no-cage rollers on one-piece cranks, but they did so when plain bearings were not what they are today.

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Babbitt, originally tin alloyed with a dollop of copper and a dash of antimony, was a great bearing metal in a time of less precisely made cranks, low speeds and poorly filtered oil. It's soft enough to yield to any high spots on a journal, and grit just disappears into the stuff. Unfortunately, babbitt yields like putty under big loads; and its yielding nature makes it quick to fail through metal fatigue.

Developments that began in 1934 resulted in today's inserts, which have thin layers of soft bearing metal on a steel backing strip. Insert-type bearings typically have a thickness of 1.5 to 2.0 millimeters, and the larger part is steel. Insert bearings are made by coating steel sheet with a thin layer of softer bearing material, then shearing the steel into strips, the strips into short pieces, and bending the pieces into half-hoop forms. To keep the bearing inserts from turning with the crank's journal, a tab is bent slightly outward at the insert's end and fits in a slot in the bearing cap. Dowels can be used for this purpose, but the tab is more common.

Babbitt is still in use as the bearing overlay on inserts for low-speed and low specific output applications, which means you won't find much of it in motorcycle engines. Copper-lead has been widely used and combines the conformability and embeddability of babbitt with the greater mechanical strength of copper.

Another qualifying property of bearing metals is that they must not friction-weld themselves to the shafts they're supporting. A steel bearing would have plenty of strength, but the inevitable friction hot spots would cause destructive metal transfers between it and the steel shaft.

Perhaps the most important, least mentioned characteristic of bearing metals, and to a lesser degree, shafts, is that they wet readily with lubricant. Cast iron has this property in a high degree, which makes it a fine material for cylinders, cams and cranks, when moderate loads are envisioned. Cast iron has been used for bearings, but it lacks conformability and embeddability.

Oiling holes should always be chamfered where they emerge from the journal. The reason is to remove a sharp edge where cracks can start.

Copper-lead bearings are not an alloy, but a mechanical mixture of copper and lead. Alloys are made by mixing one molten metal in solution with another, like water and alcohol; mechanical mixtures are more like water and oil. Copper-lead effectively is a copper sponge saturated with lead. Aluminum and tin are usually alloyed for bearing use, but have been combined as a mechanical mixture in what the Brits call reticular aluminum-tin bearings.

Tin is commonly used as a thin top coating on insert-type bearings, sometimes over a slightly thicker stratum of babbitt, which is in turn plated over a still thicker layer of copper-lead. Silver is a better material for a hard bearing's top layer, and it is used in a very few special (e.g., racing) applications.

Lubricating crank bearings has been done by a variety of means: a bunch of low-performance engines have oiled themselves by dipping an extension on the bottom of the connecting rod cap in the crankcase oil supply. The dipper splashes oil everywhere, and some of it finds its way into the bearings.

Roller-crank engines typically dribble a little oil into their main bearings, then collect the spill in channels cut in the crank webs and feed it to the connecting-rod journals. When convenient, as in singles and V-twins, the oil feed can be through a bushing to an oilway drilled into a crank mainshaft. Other drillings route the oil through a crank flywheel to the crankpin and connecting-rod bearing.

The easiest, least expensive way to oil a rod insert is with a straight hole drilled at an angle from the rod journal through the crank web and out the other side of the adjacent main journal. Unfortunately, this delivers the oil virtually at the point of maximum load under conditions of low speed and full throttle, and 180 degrees away from the load at high speeds, where inertia effects predominate.

The best place to introduce oil into a bearing on a rotating shaft is ahead of the load, but the direction of load on a connecting rod bearing is not constant. The best compromise is to cross-drill the rod journal, creating two oiling holes—each always about 90 degrees ahead of the load.

Oiling holes should always be chamfered where they emerge from the crank journal. Some believe that the chamfers aid oiling, and they may, but only marginally. The real reason for rounding the edges of the oiling hole is to remove a sharp edge where cracks can start.

Main-bearing inserts are grooved on one or both halves to create a channel for oil flowing to the hole leading out to the crank journal. In general, grooved lower main-bearing inserts are best for high-speed engines, as the full-circle channel delivers an uninterrupted flow of oil to the rod bearing. Ungrooved lower inserts provide more bearing area, but cut off oil flow to the rod for 180 degrees of crank rotation.

Little of this was known to me back when I made drawings for a crank to replace the one that kept breaking. I didn't actually get around to making the crank I drew, which probably was a good thing as my design was terrible.

I planned to make the crank from a free-machining leaded version of 4130 steel and chromium-plate the journals. Wrong steel, and wrong journal treatment—chromium does not effectively retain oil. I also planned to increase the journals' diameters and narrow them. These were both bad ideas: More diameter would have meant higher rubbing speeds and greater friction; plain bearings' edges are ineffective load carriers and narrow bearings have more edge area than wider ones.

I gave no thought to bearings, as I knew nothing about those not obvious in looking at them. I later learned, usually the hard way, that in crank and bearing technology, as in all technology, there is always more than meets the eye. It's something for all of you to keep in mind as you work your way toward being as old as I am. Maybe you can get there less embarrassed.