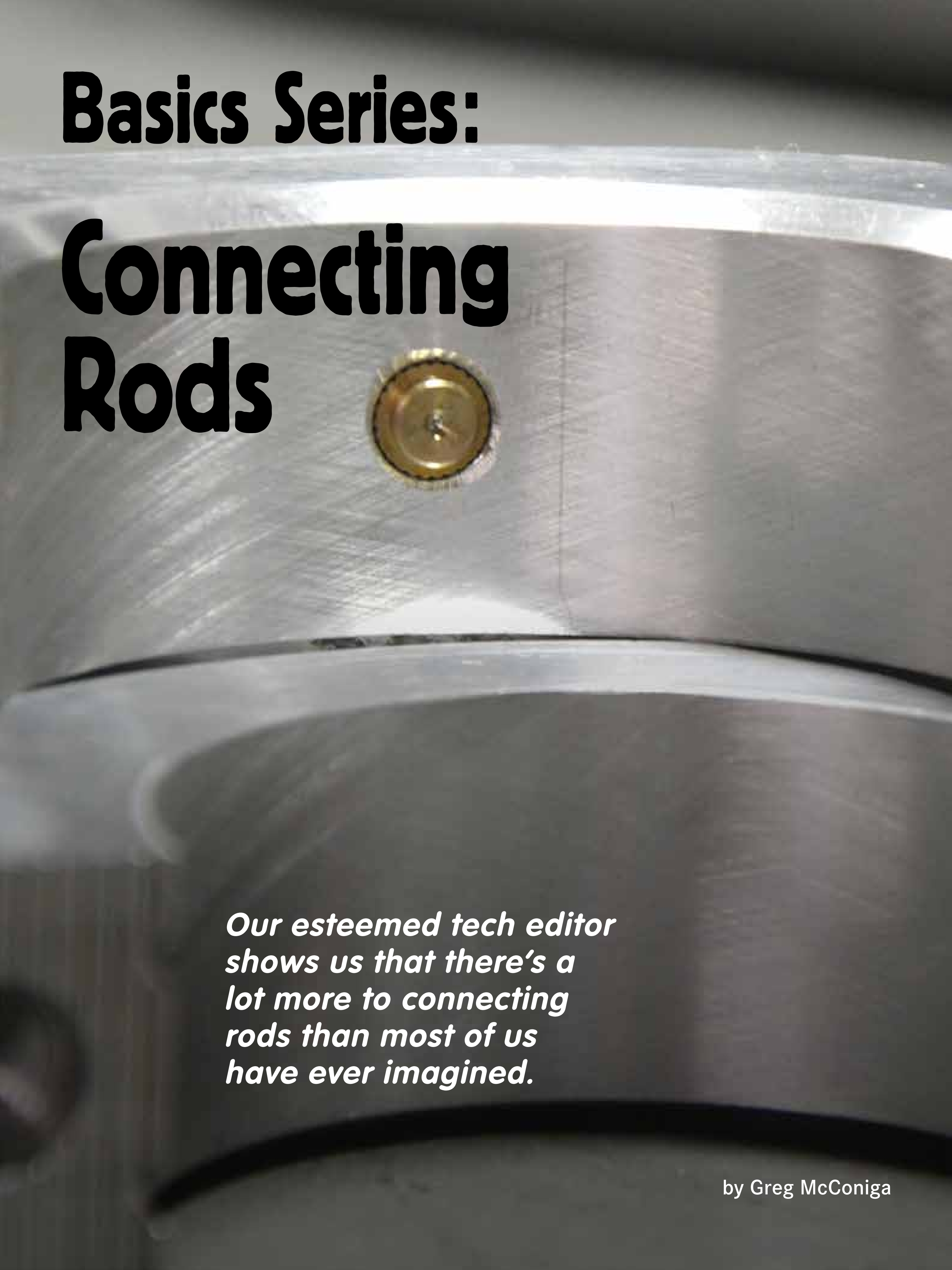
Basics Series:

Connecting Rods



Our esteemed tech editor shows us that there's a lot more to connecting rods than most of us have ever imagined.

by Greg McConiga

The connecting rod and its bolts are probably the most highly stressed components in the entire engine, absorbing the compressive stresses of compression and combustion and the tensile forces that occur as the pistons wheel over top dead center in an unloaded state with nothing to cushion or slow its movement during the end of the exhaust stroke.

You've heard of the four-stroke engine cycle, but in truth there are seven cycles on a racing engine -- or any non-two-stroke or non-rotary engine, for that matter. There are three phases to the intake stroke. The first is exhaust-driven during overlap when the negative exhaust pulse pulls through the chamber creating negative pressures reaching over 100 inches of water. That vacuum reaches right through the opening intake port and jerk-starts cylinder fill, then is followed by the normal pumping induction that occurs as the piston falls, pulling mixture into the cylinder at something around 10-20 inches of water vacuum. Final cylinder filling continues even after the piston reaches BDC and begins its upward journey. This is due to inertial ramming caused by the weight of the inrushing air fuel mixture, often lasting for as long as 60-100 degrees ABDC. This can occur because piston dwell over BDC is longer than dwell over TDC for nearly all engines and you'll see this if you graph piston movement relative to crankshaft degrees.

Compression follows, then the power phase that lasts until the rate of expansion of the trapped mass becomes slower than the speed of the falling piston. At that point, the exhaust valve opens and the two phases of exhaust follow: blow down, which occurs due to residual pressure, and pump down, which occurs during upward piston motion. This completes our seven cycles and the whole exciting mess starts all over again.

Controlling all of this commotion is the lowly connecting rod, the link pin between the rotating crankshaft and the reciprocating piston. The conversion of linear reciprocating movement to rotary movement couldn't occur without this critical link in a piston engine. The forces battering the connecting rod alternate between compressive force (trying to shorten it) and tensile force (trying to pull it apart.)

As the piston rises on compression, it undergoes a relatively slow build-up of compressive strain, followed by the sharp spike of compression forces created when the cylinder fires and cylinder pressure rises rapidly. Forces are moderate over BDC on the power-to-exhaust transition, but shift rapidly to high tension over TDC at overlap since there's no compression to catch the piston and slow it down. Over TDC at overlap it's pure tensile stress... trying to yank the rod and rod bolts in two, and acting to distort the big end and small end as the piston moves from speeds of as much as 6,000 feet per second [Editor's Note: That's over 4,000 mph – Mach 5.2!], to a full stop to full acceleration away from TDC. It's a miracle we don't drive over thrown connecting rods more often than we do.

Left: Aluminum in tension tends to move or distort a bit more than steel resulting in a loss of radial bearing crush (all that normally retains a bearing in its bore). Aluminum rods use a dowel pin to locate and secure the lower (non-load) rod bearing so that if distortion occurs the bearing will not spin.

Gauge blocks like these, along with micrometer standards and pin gauges, are the only way to check your measurement equipment for accuracy. If you aren't measuring what you think you're measuring, you can't trust the results.

Right: This is the most expensive rod bolt I've ever held. It's a Carillo/Lentz, and they run about $50.00 – EACH! And to think I can remember using a whole connecting rod assembly that didn't cost that much. It's all about materials and manufacturing precision. Some bolts and fasteners are sensitive to the moisture in your skin and chlorine found in some brake cleaners and solvents. Make sure you know what you're handling and what precautions you must take or you can ruin a fifty dollar bolt just by holding it with sweaty bare hands. Once the bolt is oily, or if your hands are covered with motor oil, it may be safe to handle.

Connecting rods are made by a number of manufacturers; I've put the websites of some prominent suppliers at the end of this article for your convenience. What you buy and use is largely a matter of your personal preference and experience.

You need to know . . .

The key to keeping your reciprocating assembly alive is cleanliness, attention to detail, careful measurement, quality parts, and outstanding assembly techniques. Of primary importance is the selection, preparation, and technique used to install the rod bolts. In a nutshell, a rod bolt is nearly failure proof (assuming a lack of hidden defect) as long as it's properly installed and tightened and you don't stray outside of the design parameters by over-speeding the engine.

The only correct way to install rod bolts is by stretch. That is, measuring the change in the overall length of the bolt as it is

This state-of-the-art aluminum connecting rod is suitable for street use, according to the manufacturer. Made of forged aluminum it features ARP fasteners and uses a doweled lower bearing to positively control bearing retention and location. It is also extremely light compared to a comparable steel rod. The extreme clearance problems we used to see around the block skirt, bottom of the bore and cam have largely been fixed by better rod design, so using aluminum rods isn't the challenge is used to be.

preloaded. What we must do with a rod bolt is preload it to a higher load than the cyclic load to which it's exposed. If we do this, the bolt will not see the cycling load at all. The bolted joint becomes one piece – solid -- for that particular cyclic load. By preloading the fastener we force it to act more like a spring

This is a racing connecting rod for a Briggs & Stratton -- Okay, I'm kidding. This is an extreme example of a connecting rod from a seven and a half by seven inch Waukesha industrial engine. I've had it for years and I pulled it out just so I could show you another world of connecting rods. It measures 18 ½ inches from center to center, uses four rod bolts and it's gun drilled to provide lubrication up to the pin bushing and the piston oil spray nozzle.

Right: Setting fixtures are invaluable when you begin measuring down to the nearly 1/10,000th of an inch. By continuously checking during the measurement process, you can verify that you are aren't getting any "drift" due to temperature changes or tool bump.

Right: Here are four examples I scrounged up from the shop. From the left there is a badly damaged Carillo H-beam rod, a Manley H-beam, a Bill Miller Engineering forged aluminum rod, and an Oliver Billet I-beam rod. If you slice across the beam and look at the cross section it will resemble either the letter "H" or the letter "I", hence the name. The "I" beam is generally heavier and stronger than the "H" beam.

Lubrication failures in racing engines are not a good thing. This Carillo was damaged when the dry sump oil pump drive belt was destroyed by track debris at 9,800 rpm. You can't lift fast enough at that engine speed to avoid the damage. At rpm like that the balance between component weight and strength are primary concerns. Pistons, pins, rods, and valves -- everything has to be light . . . and strong. The standard racer's parts weight check: If you throw it up in the air and it comes back down, it's too heavy!

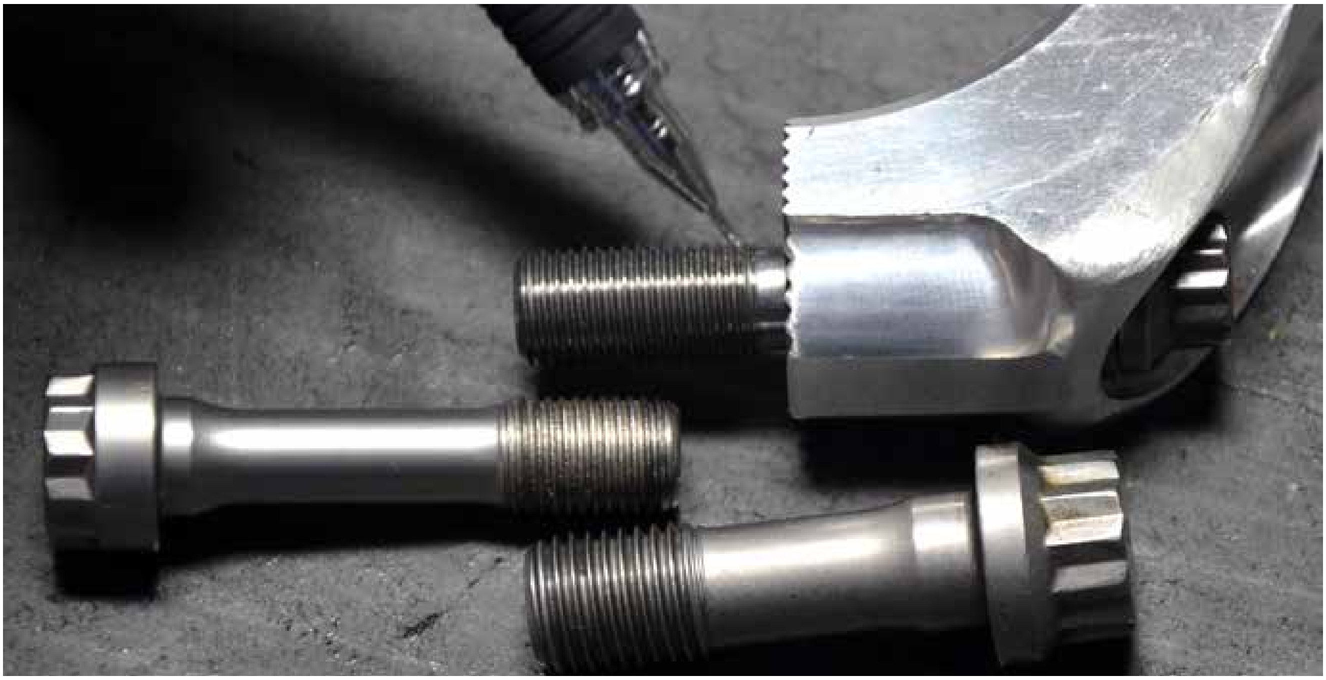
It's not uncommon to begin to see fretting and micro-welding occurring in high-horsepower applications. There are a lot of things moving and vibrating inside that engine under full load. Over three or four seasons you might notice small areas of fretting and micro-welding starting to appear. Eventually parts will have to be re-machined and bores trued.

Right: Liquid is essentially non-compressible (less than ¼ of 1% of its volume), to which this connecting rod bears testimony. A small coolant leak developed and suddenly we have a little lower compression ratio in one cylinder. Racing rods are tough and will often bend considerably before breaking.

than a solid object; the cap and beam of the rod appear to be one solid piece. This is not something that can be accurately done with a torque wrench, which is more affected by thread and bolt under-head friction than by actual fastener loading. As you increase torque, this actually gets worse.

Using high-tech, manufacturer-specified lubes helps attain consistent tightening and reduces preload scatter, but it doesn't eliminate it altogether. Most high-performance rod bolts have stretch specifications of something around .004 to .007 in. depending on the bolts and application. The stretch window is very small, sometimes as little as .0004 in.; that's 4/10,000ths of an inch. In one application I use, the window is .0052-.0057 in. Cheap tools, technique, dirt, even oil becomes a factor when reading that small a dimension, and every bolt in every application has a different specification. Don't guess. Go to the websites or make a call and get the exact specification for your application. Always use the lube the rod and bolt supplier specify

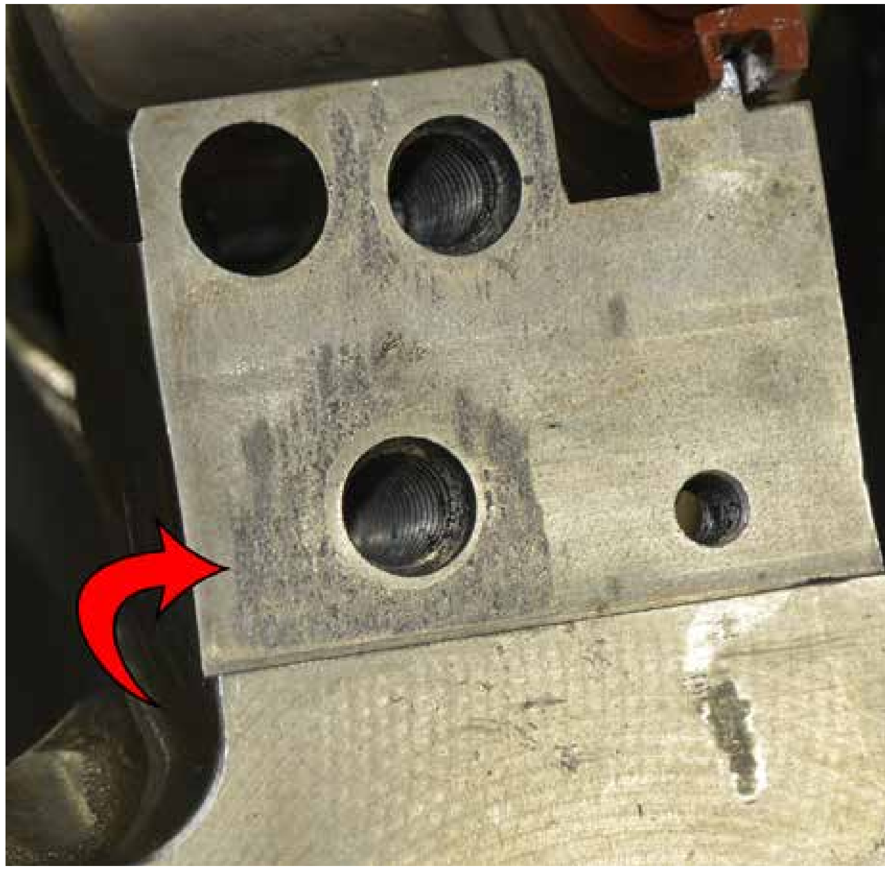
Right: Even though there is a plastic insulator built onto the shaft of the dial bore gauge, I'll often use leather work gloves to help keep the heat of my hands from affecting my readings, especially if I have to hold the tool for a while as I take a number of readings. It's amazing how much variation in readings you can get with changing tool temperature. When you are checking bearing clearances in 10,000ths of an inch it doesn't take a lot to go from good to not so good. The lesson? Always handle the tool by the insulator and wear gloves if you're going to be hanging onto it for a while.



Comparing the engaged thread length on these three rod bolts reveals something that seems logical: The aluminum rod uses a longer thread engagement. While the two examples used in steel rods have nearly identical thread lengths, the aluminum rod has almost double the thread engagement. If you're threading into a softer material, you'll need more thread engagement to hold the torque without stripping. Makes sense to me.

You can see how much bigger the rod big end is to accommodate the material strength and distortion characteristics of aluminum versus steel. You can also see how carefully shaped the upper shoulders of the rod are so these newer designs don't take near as much effort to install. Watch the clearance on the cam, bottom of the bores, and the block skirt areas.

because they have tested it on that bolt with that rod and they know that the torque or torque-plus-turns specification they give you to achieve preliminary stretch will work without overstretching the bolt. DO NOT experiment with home brews or cross-source lubes -- use what they tell you. They have ruined and tossed enough bolts finding the right combination that there's no point reinventing the wheel.



As the power levels go up, seeing this isn't completely unexpected. Even with billet caps, four-bolt mains and half-inch studs if you make enough power you're going to move things around. After three seasons this rear main cap shows what happens when you "shake things up a bit."

If you over tighten a rod bolt, you must relax it and re-measure it. If its relaxed length increases by as little as .0005 in., you may be required to discard it. In my experience, most bolts that are properly stretched will actually shrink in length when relaxed by about .0002-.0004 in., and I'm not sure I know why that is. I just know that I've got a modified ARP stretch gage that I've mated with an SPI dial indicator that will read to 5/100,000ths of an inch, and I've noted that nearly all rod bolts shrink slightly when properly stretched and cycled a few times. In the Navy, we called this PFM (Pure Freaking Magic), and while it's not a scientific term it can be used to explain all sorts of mysteries...

To correctly tighten a rod bolt, you must lube threads, under the head, and the face of the cap with the approved lubricant. Turn the bolt in one smooth motion -- do not stop -- measure, pull again, measure and so on, a technique I call "chasing the stretch." The reason is simple: Once you have pressure on the threads and on the interface between bolt head and cap, as you try to continue tightening the first thing you're doing is winding up the bolt shank before moving the threads, inducing the kind of stress that produces an early failure. If you undershoot the spec, back the bolt all the way off, relube the area under the head of the bolt, increase your torque reading or the degrees of turn, and start again.

After opening up boxes and plastic bags, washing, and drying, the next step is inspection. Even the tiniest, slightest nick in a rod beam will create a stress riser that will eventually cause the rod to break. If you find something, you must use a stone to smooth and round the nick to eliminate the stress riser. Sharp edges are bad, but round smooth curves are good. Not just here, but everywhere inside your engine. Check that all surfaces appear to be in a "finished" state, check locating dowel, locating tabs, check that chamfers are correct, and that bores and overall lengths are what you ordered.

Left: Oil feed into the rod bushing may be done from above or below the pin boss. Some rods have a hole drilled on top with a chamfer to collect oil, others drill into the four or six o'clock position on the boss and rely on splash to force oil into the pin bushing. Either way works as long as the holes are drilled all the way through and the bushing hasn't rotated to close off the hole (something to check during each seasonal overhaul).

Types, advantages and cautions

There are three materials that I'm aware of that are used to make connecting rods: steel, aluminum, and titanium. Most of us will end up using either steel or aluminum as titanium is generally considered cost-prohibitive. Steel has the advantage of strength, relative affordability, and durability. The disadvantages are the finished weight of the connecting rods and the fact that they are stiff enough to transmit everything happening in the combustion chamber right into the crank, and ultimately into the valve train. Titanium is light and strong, but it's expensive as hell and it galls easily, so lubrication must be spot on and the oiling system must be superb at stripping entrained air. Aluminum rods are light, strong (when increased in cross section), and absorb and soften combustion energy, which makes them perfect for blown alcohol, fuel and wild nitrous combinations. On the other hand, they have to be replaced

Connecting rods try to collapse inward at the parting line under tension, so keeping the parting lines solidly locked together is critical. Steel rods most often use dowels, but more interlocking surface area is engaged if you have precision machined serrations like these.

Here's a close-up of those serrations on a Bill Miller connecting rod. Very pretty work and very effective at keeping the softer aluminum rods from pulling in when the rod is under tension. If the sides pull in, they form a squeegee that wipes the oil from the journal resulting in rod bearing failure from lack of lubrication.

How big do connecting rods get? A LOT bigger than this one! Shipboard recip engines measure their bore and stroke in feet! This Waukesha rod measures about 18 ½ inches center to center and it's a good example of an "I" beam rod. It's a doozy… the engine it came out of was for power generation in an apartment complex and it ran at around 800 rpm.

much more frequently than steel or titanium, which increases operating costs.

Your choice of material, length, and sizes are determined by your application. Connecting rod selection isn't something you just go grab and then try to make everything else fit. Think deck height, compression height, stroke, fuel, application (drag or duration), blown or naturally aspirated (you can go with a lighter rod with a blower since intake pressure cushions the reciprocating assembly over TDC overlap) and rpm before you land on the rod you should use.

Prep and checks

Whenever new parts arrive, always decant them and count. Got everything? Two bolts per rod? One pin per piston? Thirty-two Spirolox of the right thickness? Check them in and look them over for shipping damage. Wash and inspect for nicks, dents, dings and anomalies and check that the bearing offset chamfer is machined in. Clamp two rods in a vise next to each other as they will be on

The only acceptable marks on a connecting rod beam will be the tiny dent you see here, left behind by a hardness tester used to check the Rockwell hardness of the finished product. Any mark, nick, or dent on the beam edge will certainly cause rod failure.

Before there were affordable connecting rod options, this was the treatment most often used to increase the reliability of stock connecting rods. This is a stock forged connecting rod that has been side polished to remove any stress risers formed along the forging parting line and shot peened to relieve stress. It also has been upgraded with ARP rod bolts. Although time-consuming, it was effective: This engine has been running for over ten years and regularly hits 6,000 rpm with a 4-1/4 in. stroke.

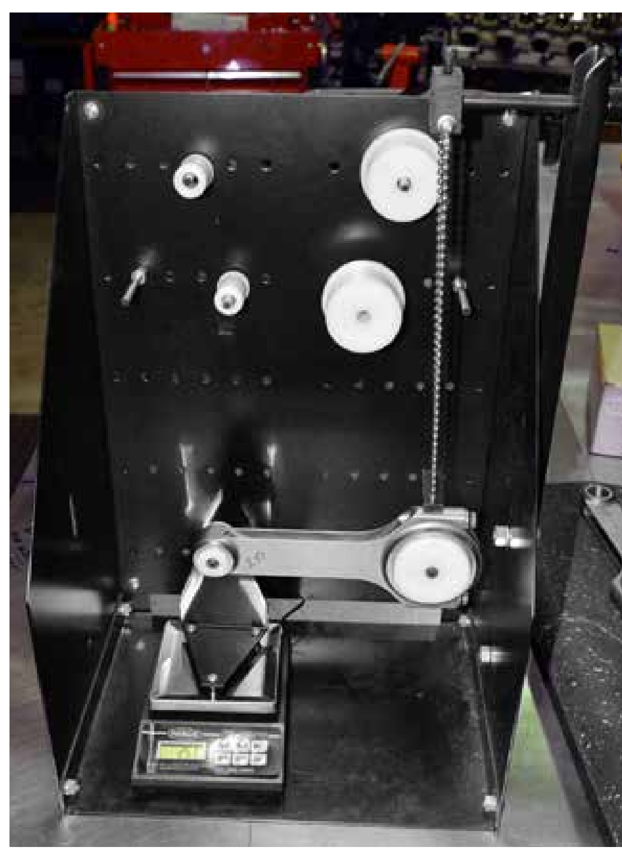
In a side-by-side comparison, the additional material used in the aluminum rod is apparent. The beam is thicker and the material around the crankpin and piston pin bores is thicker as well. Even so, it is much lighter than its steel counterpart.

the journal, measure overall width of the two big ends, and check to see that this is .010-.020 in. less than the crankpin length as a preliminary side clearance check. Inspect the pin end and make sure the bushing oiling hole is drilled and lined up. Take a look at the parting lines on the cap and rod -- dowels in place? Is the through hole in the cap relieved to clear the rod bolt radius? Everything final machined, straight, and smooth? Bores show hone marks as they should? Verify that the rod bolts are at full torque and measure the big end and pin end bores for dimension and concentricity, and calculate pin clearance for your application (more power means more clearance since you're trying to compensate for bending forces.) Verify that both bores are round. There ARE exceptions to this. There are some very, very exotic high-end rods out there that may not have perfectly round bores, but unless you're running Pro Stock, F-1, or NASCAR, you're not likely to run into those exceptions.

The total rod weight will be the same as the total of the small end and big end weights. That's how you double check your balance figures.

Mark rod bolts by location. I mark them 1 and 1L, 2 and 2L and so on for rod one opposite bearing locator tab slots and 1L for the bolt on the same side as the locator tab slots. Measure the overall length of the bolts and record that measurement. I set up my ARP stretch gauge with gauge blocks and record how much over or under my bolts are from that standard. Normally I use a 1.0000 and a 7.5000 standard for a total of 1.7500 inches and then record the over/under deviation for all my bolts. I've tried using micrometers, thread micrometers and height gauges, but nothing I've tried is as accurate as this method.

Inspect rod bolts for proper radii under the bolt head, properly-formed threads, and make sure bolts are completely free of nicks or dings. Cycle rod bolts five to seven times using the recommended lube at 70% torque to polish the thread ramp and the under-head-to-rod cap interface. It's extra time and some say that with the new lubes it's not needed, but my experience tells me otherwise. I get a much more consistent final


Right: Using a balancing fixture to measure each end of the connecting rod. Adding the weights together should equal the total rod weight.

stretch when I prep the bolts like this. Finally, run the bolts up to full stretch, loosen them and recheck overall length. Discard any bolt that remains .0005-.001 in. longer than your original measurement. You DID buy two extra "insurance" rod bolts, didn't you? Nothing worse than being in the middle of your build with a bolt that failed first stretch and no

Left: The nice part about big parts is that it's easy to see things. Here you can see the annular groove in the pin bushing that directs the oil into two oil slots on the top, or load side, of the pin bushing. The groove also directs oil up to a sprayer nozzle that sprayed oil up onto bottom side of the piston head for cooling. Big and strong… built to last long.

I replaced the mechanical .0005 inch-reading dial indicator that came stock with my ARP stretch fixture with an electronic SPI dial indicator that reads to 5/100,000ths of an inch. I can test it for accuracy with the gauge blocks shown elsewhere by simply zeroing it at one length, adding or removing gauge blocks of a known thickness and checking that the dial indicator reads the difference accurately. If you're trying to hit a .0004-in. window, your tooling must be accurate enough to do the job and you have to be able to prove that your tooling works as it should.

spares . . . it doesn't happen often today, but it can happen. In fact, that's something else to remember: Not every bolt is exactly the same, and they don't all stretch to exactly the same spec at the same amount of rotation. Start conservative and work your way up. Better to stretch them a couple of times and sneak up on it than to overshoot and ruin a bolt.

It is possible to set a dial bore gauge with a micrometer, but it is a pain and it takes time. A checking and setting fixture like this really speeds the process. The vertical fixture holds a combination of gauge blocks equal to the diameter you want to measure, and you set up your dial bore gauge by measuring between the lower and upper pad. You can also check micrometers with gauge blocks, or use them to space parts during mockup.

And In Summation . . .

Detonation, loss of lubrication, improper oil clearance, improper bolt preload, and over-speeding are the Big Five causes of rod failure, with 80% probably belonging to a loss of lubrication. You might see a product defect once in a blue moon, but it's not likely. With good inspection and

Below: As painful as it might be, good tools aren't cheap and cheap tools aren't good. We use a torque wrench to turn rod bolts, but the actual torque reading isn't as important as using the wrench to get the end result, which is proper stretch. This electronic Snap-on is extremely accurate and features a built-in angle meter that allows me to accurately record how much I turn a fastener. It records final torque, but that's not as important as being able to turn a fastener incrementally more until correct stretch is attained. I record final torque, but only as part of the documentation process. You have to have tools calibrated periodically -- you can see the last calibration sticker on the body of the wrench.

prep, you can race a lot of seasons and never see a rod failure -- and that's a good thing! It's certainly not what we dealt with in the bad old days.

The next time you're stuffing rods and pistons into a block, just take a minute and think about the job that 800-gram chunk of steel does -- from dead stop to full velocity

Tracking rod bolt overall length is the only way to know if the bolt has been stretched or worked beyond its design limits and measuring them accurately has always been a pain. After trying granite blocks and height gages, thread micrometers (with pointed anvils to fit the dimples machined into the rod bolt ends) and other methods I finally landed on this method and it has proven to be dead repeatable. First I updated my ARP gage with a tenth reading dial indicator. Since stretch is measured in tenths and the window is often less than a half thousandth this only made sense. Next I use a pair of precision gage blocks that are roughly equal to the bolt length to set an arbitrary zero on my stretch gage. I can use those same blocks to check my calibration before, during and after each measuring session if I think I've bumped something, the temperature has changed or if the indicator has drifted for any reason. Always use fresh batteries in your indicator.

to dead stop over and over. A thankless job performed in millions of engines the world over day after day after day. It's a wondrous little link pin that makes ground transportation and racing possible.

Resources

This list is far from comprehensive. There are many niche manufacturers out there for motorsport, motorcycle, watersports, and Asian or European specialists that make parts for a narrow range of clientele. I suggest that you perform your own search for rod and rod bolt manufacturers when you begin your project. ■

A-1 Technologies (bolt and stud manufacturer, no website located.)

www.arp-bolts.com/

www.spstech.com/home/

www.bmeltd.com/

www.cp-carrillo.com/Downloads/Catalogs/tabid/82/Default.aspx

www.arrowprecision.com/content/category/9-fully-machined-forged-connecting-rods-h-beam-rods-i-beam

www.howardscams.com/connecting-rods

www.crower.com/

www.dyersrods.com/index.html

www.eaglerod.com/index.php?option=com_frontpage&Itemid=1

www.grpconrods.com/

www.manleyperformance.com/

www.mgpconnectingrods.com/

www.oliverracingparts.com/

www.rrconnectingrods.com/

http://scatenterprises.com/

http://pauter.com/parts/rods/

After calibrating to my gage blocks and getting my zero I measure each bolt and record the deviation from that zero for all bolts. I measure them brand new, after my break-in sequence (running them up to 70% of torque a number of times) and after at least one full run up to full stretch. Don't be surprised to note that the bolts actually shrink a couple of ten-thousandths after fully tightened! Once I have final dimensions I can track that bolts changes as its run. Discard if you see any bolt change length by .001". They should stretch to specification and return to original length every time. If they lengthen, toss them.