

# **Cylinder Bore Distortion**

# A look at static and dynamic cylinder bore shape issues.

Even with the best of intentions and preparation, an unavoidable degree of cylinder bore distortion is likely to occur under dynamic stress (heat and pressure). The challenge is to understand how these changes take place and to establish procedures that will attempt to minimize these changes. As the block ages and/or is exposed to thermal changes, the casting's molecular structure will change, however slightly, which will affect bore geometry.

In addition, distinct changes in bore shape will take place as the block is assembled. The clamping forces that result from the installation of cylinder heads will, in most cases, cause the bores to "morph" as the fasteners pull and squeeze metal adjacent to the bores. Sometimes these changes are

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insignificant, while in other situations, the change can be so dramatic as to cause measurable ring dragging and subsequent loss of power, fuel economy and sealing due to both out-of-roundness and frictional heat. In some engines, these problems may be compounded if the specific block is severely affected by additional distortion that results from clamping forces caused by bell housing bolts, water pump bolts, motor mount bolts, etc.

Granted, only the more severe cases will be a cause of concern on a street engine. However, if the goal is to produce an optimized racing engine, every factor which can affect dynamic ring shape must be considered.

As noted by Sunnen, in order to accurately "map" a cylinder bore in order to obtain a clear dimensional picture of how that bore is shaped from top to bottom, a special "PAT" gauge is used. This is an inclinometer that features a shaft and probe. The shaft is affixed to the deck or torque plate and runs vertically through the bore centerline. The probe runs along the shaft vertically and monitors the bore walls radially. This provides a dimensional perspective view of the entire bore, relative to the theoretical bore centerline. Don't expect to run out and buy one of these, as they cost around \$175,000 and are primarily used by piston ring and honing equipment manufacturers for analysis applications. This allows plotting the

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This stress graph illustrates how a cylinder bore may be distorted from round to out-of-round as a result of head fastener loads. (All illustrations provided courtesy of MAHLE Clevite.)



This dimensional "isometric" view further illustrates static dimensional shift that can occur from cylinder head installation.

actual shape of the bore in addition to bore diameter. The readings can be displayed radially (viewing the bore from overhead) to show where the bore shifts from the centerline; and in an isometric view (side angle perspective in a variety of view angles) that allows you to see the entire bore in a dimensional manner.

In order to obtain bore diameter readings in your shop, without the use of this sophisticated equipment, the cylinder walls can be measured with a bore gauge at four different levels at four clock positions (12, 3, 6 and 9 o'clock). Once these numbers have been recorded, place a honing plate (one per deck) on the block, torque the plate(s), and re-measure the same points to reveal differences that have occurred. However, bear in mind that this will not reveal concentric bore diameter shifts relative to the centerline.

Another variable relating to bore distortion is the cylinder head itself. After measuring the bores (accessing from the bottom of the bores) on a relaxed block (no heads or torque plate), install and torque a cylinder head, and read the bores again from the bottom of the bore to note the changes that have taken place. Next, remove that head and install a different head of the same type and measure the bores once again. If you find a different distortion level/pattern, don't be surprised. Depending on the makeup of the cylinder head, the clamping forces may reveal a different situation due to the structure of the head, especially on cast heads, due to differences in the hard/ soft internal makeup of the casting core. If the head pulls down harder or softer in various areas, this will accordingly affect how the block is stressed, resulting in variations of cylinder bore shape.

As mentioned earlier, when measuring a bore for shape, we need to remember that, depending on the instrumentation being used, we may or may not obtain a true bore shape. If we use a bore gauge, we are simply measuring bore diameter (and out of round) in specific height levels of the bore, but since we are not referencing from the true bore centerline, we may be overlooking shifts of the centerline at various height locations. If in doubt, or if we know that the radius of the bore has shifted relative to the centerline, we can use a precision boretruing fixture to correct the problem (such as those offered by BHJ, CWT, etc.), or take advantage of CNC technology in order to create a "new" bore centerline based on blueprint data from the block manufacturer. The bores can then be "clean-bored" to an oversize, with the cutters referenced from a fixed (and presumably correct) centerline. This will create bore trueness in a static condition, but subsequent changes may still occur when the block is subjected to loads, pressures and temperature.

Keep in mind that when we're dealing with cast iron blocks, the very nature of the casting process and the material mix can and will create differences from block to block. In other words, if you lined up five blocks with identical casting numbers and identical age, you'll probably find five different variations of bore distortion. Knowing this, we need to temper our view of block analysis. Just because one small block Chevy of a particular series and casting shows unruly bore distortion in number 3 bore, this does not mean that this condition will be exactly repeated in every block of that vintage and type. Each block casting is its own animal and needs to be treated as such.

Mahle-Clevite's industry-respected Bill McKnight was kind enough to share bore distortion information that was part of a previous Dana/Victor/Clevite NASCAR engine builders' seminar presented by Victor Reinz engineer Ernest Oxenkonect, which addressed this very topic. Selected excerpts from that seminar follow.

Primary causes of bore distortion in relation to the cylinder head/block joint include clamping load, cylinder head gasket/combustion seal design, the honing procedure and assembly procedures.

#### **Clamp Load**

Bore distortion is generally directly related to clamp load. The clamp load must restrain combustion lift-off force and still provide adequate force for the gasket to do its job. Additional clamp load generally only leads to additional bore distortion. In other words, tightening head fasteners beyond the recommended specification will only hurt. The optimal goal is to minimize clamp load and distribute the clamp load uniformly while maintaining combustion and fluid seals.

Distribution of clamp load affects bore distortion. An equal load distribution is the goal.

One interesting item to note is that the end cylinders are typically over-loaded, as they aren't required to share bolt load between cylinders. For custom racing applications, consider smaller diameter studs/bolts for deckend positions to reduce the tendency of over-loading the end cylinder areas. An excellent method of checking this is to perform pressure film studies (carbonless impression paper) to inspect head gasket





It's common practice for builders to install a deck plate prior to honing. However, it's more desirable to install two deck plates (one at each bank) to more closely simulate the stresses that the block will incur when it is assembled. Photo by author.

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load distribution, in an effort to equalize loads by possibly using smaller-diameter fasteners at end positions.

Bolt clamp load can be measured by referencing bolt stretch (in terms of length). This is done with a Bidwell Bolt Gauge (formerly known as a Raymond Bolt Gauge), which sends an ultrasonic wave signal through the bolt from the head (or top of the stud). Once this signal travels down to the bottom of the bolt, it then shoots back to the signal sensor. The amount of time that is takes for signal return determines length, or amount of stretch. The bolt is first measured statically to create a reference value, which is then compared to stretched length under installed conditions. The final value can be measured in terms of pounds of clamping load. For example, if a 7/16" bolt is rated at 10,000 lbs and the installed reading shows a clamping load of 12,000 lbs, it's obvious that the bolt has been stretched beyond its clamp load design. Also, bolt load can be tailored to achieve a uniform distribution of clamp load across all areas of the deck and head gasket by experimenting with monitored bolt loads while using a telltale load indicator such as carbonless impression paper. Determining bolt load knowledge is a critical factor and should be gathered on engines both during assembly and during disassembly.

Note: By the way, if you're interested in obtaining a Bidwell bolt gauge, contact American Bolt Tightening at 734-591-2055. The units run around \$20,000, so while they're not for every shop, operations building \$30,000-andup race motors may want to consider the investment. If you plan to achieve optimum cylinder head clamping and minimal bore distortion by precisely verifying bolt load, it's a must-have piece of equipment. I had the opportunity to watch one of these gauges in use during a race engine build seminar at the Dana school two years ago. The gauge is easy to use and is extremely accurate (it should be, considering the price). There's nothing wrong with a torque wrench when used for intended applications, but at the highest level of race engine building, you really need to know what the bolt is doing internally when it's securing the cylinder head to the block.



## **Honing Assembly Procedure**

Install a deck plate (torque plate) and head gasket to initial assembly load. Next, relax the clamp load to levels actually measured from a conditioned engine. Hone the cylinders at this point. Assemble the engine to exact initial clamp load of the data-bearing engine.

Torque values are not adequate when performing assembly where optimal performance is required, and where exacting bolt/stud load must be accurately measured. Torque and torque/ angle methods can result in 25 – 30% load variations. Instead, measure bolt/ stud load with an ultrasonic gauge.

Simulating operating cylinder head load on bores while honing is the most critical factor in minimizing bore distortion. Again, this means going beyond merely using a deck plate with bolts torqued to value. Actual bolt loads must be monitored and achieved at predetermined levels.

#### How much is enough?

Minimum clamp load must be greater than the combination of lift-off force and required sealing force.

A general approximation (a good general model) for clamp load is 3x's liftoff force. This generally results in static sealing stress in the combustion area of 7500 psi. Lift-off force for a 4.25" bore @ 1400 psi peak pressure is19,861 lbs. Depending on the application and number of bolts featured to seal each bore, individual bolt load requirements may be in the 6165 – 11,917 lbs range. For example, a typical ARP 7/16" stud may be rated at 12,700 – 15,600 lb load range.

#### Head Gasket Selection and Consideration

Wire ring style head gaskets may relax as much as 10 - 25% after initial assembly. By contrast, MLS gaskets relax less than 10% after initial assembly, thereby providing additional assurance of maintaining proper clamping load and load distribution.

Wire ring style gaskets require the highest clamp load and can feature high peak loading along the cylinder openings. Again, by contrast, all active (spring function) MLS gaskets have the lowest peak loading along the cylinder openings. MLS gaskets with a builtin "stopper" layer or beaded spacer provide high combustion sealing stress with lower required bolt loading. Active MLS gaskets are designed with formed metal layers featuring contact and air



Three views of a "typical" dynamic bore distortion scenario.



This graph illustrates how cylinder concentricity can be affected by the head clamping operation with regard to temperature and operation with regard to wall temperature and gas pressure.



These isometric views show bore shape changes relative to temperature shifts.

spaces that work as a spring to provide compressive tension that aids in sealing while requiring lower loading. Active MLS gaskets feature an elastic element which absorbs cylinder head motion. Stopper MLS gaskets also feature a layer of "dead stop" that provides a limit to compression. Stopper type gaskets feature rigid combustion seals which bend the cylinder head over the seal as a result of clamping loads. Active MLS offers low hardware distortion, since the gasket "gives" to reduce the chance of distorting bores and head decks. This type also provides good recovery for lightweight hardware. However, it may be difficult to generate high combustion sealing stress with an active type MLS. The stopper MLS type of gasket provides high sealing potential, but has the potential to generate high hardware distortion. Determining which type of gasket to use will be based on research data gathered during engine components, engine test assembly and engine operation (on dyno and/or on-track).

# Thermal considerations during honing

Another aspect of obtaining a bore that will remain as true as possible during engine operation involves heat. Consider that while a bore may be correctively trued while the block is cold, it stands to reason that bore shape may be affected as temperatures rise and fluctuate. In that regard, does it make sense to hone cylinders at room temperature, or at an elevated temperature that more closely resembles levels experienced in a running engine? Some argue that the change is minimal; or that the act of honing generates surface heat on the walls anyway. However, others are of the opinion that the block should be heated with circulating water in order to replicate the effects of hot coolant flowing through the block (and adjacent to the bores).

While a torque plate affects the upper 1.5" or so of the bore, the dimensional change of an average bore between hot



This example illustrates a "before & after" axial view relative to hot honing.

and cold can be twice that of a torque plate, or more. Because of the complex interaction between engine design, casting processes, uneven wall thickness, variations in metal composition and internal metal stresses, dimensional changes of the cylinders within a block can vary significantly. Not only are there thermal dimensional changes, but these changes are far from uniform throughout the bore. The major effect is the gross dimensional change in bore diameter, which can change .0005 - .001" of an inch, per inch of bore diameter, at temperatures between 65°F and 210°F. For a common 4" bore, this equals .002 - .004" of growth.

The rest of these variations within the bore...thermal distortions.... are largely non-uniform and can create critical concerns. These distortions include the local diametric variations in the walls, the barrel or hourglass effect, bores departing from circular and becoming non-round and the bowing or arcing of the bore from a true cylinder. A normal

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bore gauge can detect all but the last of these distortions.

Since the cylinder walls are not of uniform thickness and the cylinder is captured at each end, thermal expansion of the metal can and does cause distortion of the cylinder walls. A normal cylinder wall will assume a slight barrel shape as the temperature increases, with high and low spots that vary from cylinder to cylinder, causing a non-circular, non-uniform bore as the engine heats.

Temperature is not the only effect on a bore. Under normal conditions, the engine cooling system operates at 10 - 14 psi. Normal engine pressure forces the cylinder into an hourglass shape. While 10 - 14 psi may not seem like much, it compresses the cylinder walls in the center around .0005". The normal pressure effect from the cooling system tends to partially offset the barrel effect of this thermal distortion. Because of these offsetting effects, hot honing must be done with the block pressurized to achieve the best possible true bore.

While a few attempts at creating a "hot honing" environment have been seen in previous years, an excellent example of a viable system is KW Products' "Hot Hone 2000." This is a completely self-contained system that features a stainless steel cartridge pump, brass tank and armored safety hoses with quick ("Kwik") connect couplings. The system includes a fully adjustable electronic thermostat, pressure and temperature gauge, automotive-style filler, soft plug and block adapters for the small block Chevy. According to KW, the unit is adaptable to all honing machines and uses standard torque plates. Block adapters for other engines are also available or can be fabricated by an individual shop.

## Various factors can affect cylinder bore geometry changes

#### Factory original cast blocks:

- The density of the material varies
- Core thickness varies throughout
- Machining tolerances are not within acceptable performance guidelines
- Webs or reinforcement of critical areas are not optimal
- All core sand, ties, stands and machining debris is not removed
- Galleys are not sized or routed optimally
- Water jackets and passages do not allow for even heat transfer
- Flow problems in molds create weakened areas



ABOVE: The hot honing unit is plumbed to the block on the honing machine. The theory is to attempt to simulate engine operating temperature (at least in terms of coolant temp) during honing. RIGHT: Sunnen's hot honing water heater/delivery unit. Photos courtesy of Sunnen.

#### Aftermarket blocks (all materials):

- Some are just copies of OEM and suffer the same ills
- Some are far superior in most of the above areas.

Torque plates reproduce the stress in the upper 0.5 - 1.5" of the bore that would otherwise be produced by bolting the cylinder head in place while still allowing access to machining the bore. The actual measured amount of distortion in the areas around the bolt at the top of the block is seldom more than .0005 - .001". This is however a significant amount when you consider that the average high-performance engine builder won't accept a bore that is less than .0002" straight and true.

It is usually necessary, especially with plain-Jane OE blocks, to torque-plate the block when you bore it if you plan to use torque plates when honing. The hone may jerk from the distortion if it wasn't originally bored with torque plates and sometimes the bore is distorted enough that by the time the machinist straightens the bore, it may be larger than desired.

When a block is heated to its intended operating temperature and the subsequent related pressure, the amount of distortion will vary depending on many factors. An obvious few are temperature, pressure, block material, varying density of material, quality of casting, Siamese bores, sleeved blocks and offset boring.

The average change in size of a cylinder bore heated to 190°F from an

ambient temperature of 65°F is between 0.003 - 0.004". This anticipated change is not necessarily linear, as different areas of the cylinder bore may change by varying amounts.

According to research done by KW, in addition to the amount of average bore size increase, the average difference from cylindrical in the heated and pressurized bore seems to be around .0015". This change can be several times the change seen with torque plates. These are average figures and the real revelation will be those areas of the bore that move outside of these norms without obvious reason.

Theoretically, with the engine block heated to operating temperature during the honing process, the bores should remain fairly stable and stay on-size throughout the process.



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