

New Metals, New Challenges: Understanding The Metallurgy In Today's Engines

By Larry Carley

Cast iron is like an old familiar friend to most of our readers because it's been around forever. Vehicle manufacturers like cast iron because it's cheap compared to most other metals, it is strong and durable, and it can be easily cast and machined to make engine blocks, cylinder heads, crankshafts, connecting rods and other engine parts.

But as automotive technology continues to move forward, other metals have been replacing ordinary cast iron in many applications.

Such "new" metals as high silicon alloy aluminum for engine blocks, aluminum metal matrix composite (MMC), discontinuously reinforced aluminum (DRA), and nickel plated aluminum blocks and cylinders, compacted graphite iron (CGI) engine blocks with or without nickel plated cylinder bores and even bimetal engine blocks made of cast magnesium around aluminum cylinders are finding their way into your shop more often.

Powder metal parts that mix iron with other metals are being used in more and more production engines for everything from valve guides and connecting rods to timing gears. In high performance and racing engines, exotic metals such as titanium are now commonly used for valves, springs and retainers. Ceramics, carbon fiber materials or even high temperature plastics may be in tomorrow's engines. Concept engines have been constructed from all of these materials as engineers continue to push the envelope for lighter, stronger and better materials.

CAST IRON

To better understand some of these new metals, let's start with that metal our readers know well: cast iron. Actually, cast iron is not one metal but a whole family of iron-based metal alloys that contain iron and carbon. There are hundreds of different cast iron alloys, but the kind that's typically used for standard engine blocks and heads is gray cast iron, which is about 92 percent iron, 3.4 percent carbon, 2.5 percent silicon and 1.8 percent manganese. Gray cast iron has a tensile strength of around 25,000 psi and a hardness of around 180 on the Brinnell scale.

Gray cast iron tends to be a brittle material and can crack and break under stress. Iron also rusts, which means aqueous cleaning requires a follow-up treatment with a rust preventive or bead blasting. Same goes for thermal cleaning which leaves a powdery rusty residue on the surface of the parts. Cast iron parts also have to be painted, plated or powder coated if they will be exposed and you don't want them to rust.

Gray cast iron is relatively easy to machine with carbide abrasives or cubic boron nitride (CBN), and cracks can often be repaired by pinning. But cast iron is very difficult to weld and requires high temperature furnace welding, nickel brazing or spray welding. Except for diesel cylinder heads, antique engine parts or high dollar value parts, badly cracked or broken cast parts are usually cheaper to replace than to repair.

For engine parts that have to withstand higher loads and stresses such as crankshafts, camshafts and gears, a different alloy is used such as ductile or nodular cast iron. These alloys include about the same levels of carbon and silicon as gray cast iron alloys, but add traces of phosphorus, nickel, copper and other elements to improve strength and hardness. Ductile and nodular cast irons are less brittle than gray cast iron, and can have a tensile strength of 70,000 psi or higher, and a hardness of around 170 on the Brinnell scale. Heat treating can further modify these numbers to improve strength, durability and surface hardness. Ductile iron is often used for the top piston rings in high output, high temperature engines.

Because ductile and nodular cast irons are harder metals than gray cast irons, they are more difficult and time-consuming to machine. Tool wear is greater, and feed rates have to be slowed down to achieve the same surface finish. Coated CBN tool bits can prolong tool life. Grinding also works well for machining ductile iron parts.

STEEL

Steel is another type of iron alloy. Steel has been around for over 3,000 years, and was first used to make swords and other weapons that proved to be far superior to weapons made of bronze, stone or wood. It helped the Romans conquer the world, and today it's still a metal of choice for many automotive parts.

Steel's metallurgy is well understood - at least by metallurgists. They talk about things like "martensite" and "austenite" when describing the microstructure of the metal. These terms refer to the way in which the carbon is dispersed in the grain structure of the metal as the molten metal is cooled. This is very important because the amount of carbon in the steel, the presence of other trace elements, and the rate at which the metal is cooled all affect the strength, ductility and hardness of the steel.

Steel is mostly iron with only small amounts of carbon (0.2 to 0.5%) and other elements such as manganese, copper, silicon, sulfur and phosphorus added. Getting rid of the carbon creates a better microstructure than what is possible with cast iron alloys. That makes steel more ductile and stronger than cast iron. Consequently, steel will bend before it breaks. It's a great material for swords, and a great material for crankshafts, camshafts, connecting rods, wrist pins, rocker arms and other highly stressed engine parts, including the top piston rings in many late-model high output engines.

By tweaking the alloy with various elements, the qualities of the metal can be improved even more. Alloy steels include tool steels, high strength steels (HSS), spring steels and more. Silicon, for example, is added when making spring steel for valve springs or chassis springs. Manganese

is added to improve wear resistance. Cobalt gives high speed tool steels toughness and the ability to withstand heat. Nickel, molybdenum and vanadium reduce brittleness and increase strength. Chromium and molybdenum in combination ("chromoly") produce a very strong, heat resistant steel. Nickel and chromium together inhibit rust and corrosion. Depending on the alloy and its heat treatment, the strength of steel can vary from 55,000 psi up to 300,000 psi or higher.

Forged steel alloys are often used for highly stressed parts such as crankshafts and connecting rods in high output engines, performance engines and diesels. Forged parts are made by pounding metal blanks or slugs into shape. Pressure is applied by a megaton forging press that bangs down on the metal ("drop forging") forcing it to conform within a die cavity mounted in the press. The forging process also alters the microscopic structure of the metal itself, changing the grainy crystal structure to a stronger fiber like matrix that is more resistant to fracture or cracking. Steel may be "cold" forged or heated and "hot" forged. Hot steel flows more easily than cold steel, but cold forging can have a hardening effect on certain steels.

STAINLESS STEEL

Stainless steels contain a high percentage of chromium. Many also contain 5 percent or more nickel and trace amounts of niobium. Steel technically qualifies as "stainless" if it contains at least 11percent chromium, but it's important to note that there are different grades of stainless. Steel with 12 percent or less chromium can still discolor and won't have the corrosion resistance of a steel that contains more chromium. The "better" grades of stainless will contain 16 to 18 percent or more chromium. Keep that in mind the next time somebody offers you a box of "stainless" fasteners from Taiwan. A good way to tell the higher grades of stainless from the cheaper alloys is with a magnet. The better grades are nonmagnetic.

The primary use of stainless steel in engines is for valves. Exhaust valves run considerably hotter than intake valves (1400 to 1600 degrees F.), and therefore require a tough material such as "21-2N" or "21-4N" stainless steel. Both alloys contains 21 percent chromium. The 21-4N alloy contains about twice as much nickel (3.75 percent) as the 21-2N alloy, which makes 21-4N the better material for exhaust valves in performance applications because it can handle higher temperatures. The 21-4N alloy also meets the "EV8" Society of Automotive Engineers (SAE) specification for exhaust valves.

SAE classifies valve alloys with a code system: "NV" is the prefix code for a low-alloy intake valve, "HNV" is a high alloy intake valve material, "EV" is an austenitic exhaust valve alloy, and "HEV" is a high-strength exhaust valve alloy.

One of the advantages of using a higher grade of stainless such as 21-4N for a performance exhaust valve is that the margin on the valve head can be made thinner with less danger of cracking or burning. As for grinding, 21-4N valves can be ground in exactly the same manner as valves made of any other material.

For more demanding applications (engines with nitrous oxide, turbochargers or superchargers), higher temperature alloys such as Inconel or similar materials may be required. Inconel is a "super alloy" material that is sometimes used for exhaust valves because of its superior high temperature strength. Inconel is a nickel base alloy with 15 to 16 percent chromium and 2.4 to 3.0 percent titanium. Inconel 751 is classified as an HEV3 alloy by SAE.

Stainless steel valves are typically chrome plated to improve lubricity and reduce stem wear, and the valve head is often swirl polished to improve airflow and reduce stress that could cause valve failure. On chrome-plated valves, the coating may be .0002" to .0007" thick up to a hard plating of as much as .001". Chrome has microscopic pores that retain oil, but actually creates a slightly rougher surface finish on the valve stem. Other surface treatment alternatives for valves include nitriding and various thin film coatings for wear resistance and lubricity such as hard carbon Physical Vapor Deposition (PVD) and Plasma Assisted Chemical Vapor Deposition (PACVD) coatings. Dry film coatings may also be applied to the head and valve stem to reduce the build-up of carbon deposits on the valves, and ceramic thermal barrier coatings may be used on the valve face to reflect heat back into the combustion chamber. All of these coatings can be affected by subsequent grinding and finishing operations, so in some cases the valve may have to be recoated. When it comes to choosing valve alloys, the best advice is to work with your valve supplier. They can help you decide which alloy will provide the best value and durability for the type of engine you are building. There's no need to buy an expensive Inconel or other super alloy valve if a conventional 21-2N or 21-4N has more than enough strength for the temperatures the engine will likely produce. On the other hand, if you're building a turbocharged, supercharged or nitrous engine, you may want to upgrade to a higher temperature alloy for added protection.

Stellite is a hard facing material that's sometimes used for heavy-duty exhaust valves. Stellite is a cobalt based alloy with a high chromium content. It too comes in various grades. Stellite increases the valve's oxidation and corrosion resistance. It may also be used on the stem tip for added wear resistance.

Inconel is another "superalloy" that's sometimes used for exhaust valves because of its superior high temperature strength. Inconel is a nickel base alloy with 15 to 16 percent chromium and 2.4 to 3.0 percent titanium. Inconel valves are sometimes used in place of 21-4N stainless steel if valve wear is a problem.

TITANIUM VALVES

One of the more exotic valve metals is titanium. The metal's main advantage is its light weight. A titanium valve weighs about 40 percent less than a comparable valve made from steel. The light weight is good for more rpms, lessens the strain on the valve train and allows the use of more radical cam profiles that open and close the valves more quickly. But titanium valves are expensive (\$80 to \$100 or more each), and the price keeps going up.

As great as titanium is, there are some tradeoffs with this particular metal. Titanium valves do not shed heat as quickly as stainless steel valves, so the valves tend to run hotter. So many engine

builders use beryllium copper valve seats with titanium valves (both intake and exhaust). Beryllium copper seats have a yellow or gold appearance, and typically contains about 2 percent beryllium (though some alloys contain only 0.2 to 0.6 percent beryllium). The alloy conducts heat better than steel alloys or cast iron, tensile strength similar to cast iron, and is much kinder to titanium valves than hard steel seats. But beryllium is a toxic metal, so care must be used to avoid inhaling any dust when machining the seats. Other seat materials that work with titanium include cast or sintered iron alloys for intake valves and nickel-steel alloys for the exhaust valves. For intake guides, manganese or silicon bronze are often recommended.

COMPACTED GRAPHITE IRON (CGI)

This brings us to one of the newer, more exotic iron alloys, compacted graphite iron (CGI). This new type of cast iron was invented back in 1949, about the same time ductile cast iron was discovered. For many years, nothing much came of CGI because it was not quite as strong as ductile iron. But it was 75 percent stronger and up to 75 percent stiffer than gray cast iron. This meant an engine block could be made up to 20 percent lighter than a standard gray cast iron block - a perfect solution for reducing weight or making a block stronger to handle more horsepower.

Though still much heavier than aluminum, CGI has five times the fatigue resistance of aluminum at elevated temperatures, and twice the resistance to metal fatigue as gray cast iron. When used in a diesel engine or a racing engine, it can provide a significant savings in weight.

Many Caterpillar engine components are being switched to CGI, such as modular heads, and Audi is using CGI in their 2.7L, 3.0L V6 and 4.0L V8 diesel engine blocks. The BMW Series 7 V8 engine is also CGI. Even Hyundai is now producing some CGI blocks (2007 Veracruz).

One aftermarket supplier of engine blocks said CGI is a good upgrade for performance applications where high levels of nitrous oxide or turbo boost are being used. The added strength provided by CGI has no weight penalty, but typically adds about 40 percent to the cost of the block over gray cast iron.

Machining CGI is a little more difficult than gray cast iron because of the increased hardness of the material. Coated CBN works well, but tool wear is accelerated and feed rates may have to be slowed to achieve the same surface finish.

ALUMINUM

Aluminum has been long used for pistons, cylinder heads, blocks and even connecting rods. Aluminum's main advantage is its light weight, which is up to a third less than cast iron. It also dissipates heat very quickly, which can be an advantage or a disadvantage depending on what you are trying to accomplish. To make horsepower, you want to retain heat in the combustion chamber. But at the same time you don't want an engine to detonate or experience pre-ignition. So for maximum power, aluminum heads are usually the best choice.

Aluminum heads "as cast" or CNC-machined with various port and combustion chamber profiles are readily available from aftermarket suppliers. One of the nice things about aluminum is that it is softer than cast iron and is easy to machine. Tool life is longer, and feed and speed rates can be increased to boost productivity. Aluminum can be ground or machined with conventional carbide abrasives, but Poly Crystalline Diamond (PCD) is the super-abrasive of choice for maximum tool longevity and production speeds.

Cleaning has always been a challenge with aluminum parts because it's hard to get a nice bright finish on dirty, stained or badly corroded parts that have been cleaned. Cleaning aluminum with an aqueous cleaning system requires using a compatible chemical that won't etch or discolor the metal. Aluminum forms an oxide on the surface that has to be broken down chemically with caustic. But caustic can turn the metal black, so that may have to be removed with a de-oxidizer treatment (typically a acid solution of some type) and/or by blasting with glass beads, aluminum shot or soft media such as plastic or baking soda (sodium bicarbonate). The nice thing about blasting with baking soda is that it eliminates any worries about glass beads or shot being left inside a block or head, it is water soluble and can be easily washed away, and it eliminates the need to prewash or bake the parts being cleaned.

Aluminum can also be cleaned in an oven, but the temperature of the thermal cleaning process has to be limited so you don't soften (anneal) the metal. As a rule, you should never heat aluminum parts in excess of 600 degrees F, and never allow parts to bake at 450 degrees F or higher for more than two hours.

ALUMINUM ALLOYS

A common alloy for casting OEM and aftermarket aluminum blocks is 355 with pressed-in or cast-in iron or steel cylinder liners. This can present a challenge when resurfacing an aluminum block with iron or steel liners. Cutting the soft aluminum and then the hard sleeves deflects the cutting action. Currently the best options appear to be grinding with stones. Ceramic inserts are not a good choice because a sharp-edged ceramic may chip like PCD when it hits the steel sleeves. A chamfered ceramic insert will cut the steel but will not leave a smooth surface on aluminum. Chamfered CBN and coated carbide inserts provide a better surface finish, but dull quickly.

Ordinary aluminum blocks without iron or steel liners are too soft to provide good wear resistance, so a special high silicon alloy aluminum must be used (typically 16 to 18 percent silicon). Back in the 1970s, high silicon alloy aluminum blocks without cylinder liners were used in the Chevy Vega. The cylinders were finished with a special honing/etching process that exposed the hard silicon particles to provide wear resistance. It didn't always work the way it was supposed to, and many of those engines burned oil from day one.

In recent years, BMW, Mercedes and others have revived sleeveless aluminum blocks, and all-aluminum cylinders are becoming more common on motorcycles and other air-cooled engines.

The high silicon alloys are still pretty much the same, but wear resistance now is being achieved by giving the inside of the cylinders a nickel silicon carbide coating.

The "Nikasil" process for coating cylinder bores with nickel silicon carbide was introduced in 1967 by Mahle. It was initially developed for rotary engines to reduce wear in the aluminum rotor housing. But it also turned out to be a good wear-resistant coating for aluminum piston engines, too. A Nikasil coating only needs to be a few thousandths of an inch thick to make the cylinder walls wear resistant (typically .003" to .007"), and the coating can be reapplied if the cylinders need to be bored to oversize. Nikasil retains oil well and allows tighter piston-to-cylinder clearances to reduce blowby. That's why many NASCAR teams are running engine blocks with Nikasil coated cylinders. It helps them make more power, and as an added benefit the blocks last longer.

One thing you have to watch out for with Nikasil is that it can't tolerate much sulfur in the fuel. BMW discovered this the hard way in the 1990s when high sulfur fuels in England and the U.S. dissolved the Nikasil coating in some of their all-aluminum M60 engines.

Special abrasives are needed to hone cylinders with Nikasil coatings. Diamond hones work best here, and the objective is to not remove as little material as possible to restore some crosshatch. The bores can be honed to a super smooth 4 to 6 microinch finish to minimize friction.

ALUMINUM METAL MATRIX

In recent years, aluminum alloys have been improved by mixing in particles of aluminum oxide, silicon carbide and graphite to achieve greater hardness and lubricity. Cast aluminum alloys are also being reinforced with graphite and ceramic fibers (discontinuously reinforced aluminum or DRA) that add strength. Honda has been doing this with some of its aluminum engine blocks, and other vehicle manufacturers are starting to use more aluminum composite materials as well.

Machining is still essentially the same, but the harder alloys increase tool wear and often require slower federates to achieve the same surface finish. Coated PCD for milling is a good choice for these applications.

BEYOND ALUMINUM

BMW is now building an engine that may be a trendsetter for what's to come. The R6 3.0L six-cylinder engine that debuted in the Z4 Roadster in late 2004 has a unique magnesium/aluminum bimetal block made of magnesium cast around the aluminum cylinders. The engine is the lightest production 3.0L engine in the world, and weighs 24 percent less than a comparable all-aluminum engine. This same engine is also used in the BMW X3 and X5 models.

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