Understanding Valve Design and Alloys

By Doug Kaufman

To the naked eye, a valve is a valve is a valve. Sure, there may be two, three, four or more of them in the cylinder head, but unless you have x-ray eyes, one alloy looks pretty much the same as another.

The importance of coatings to today's valves should not be overlooked, of course. Coatings on titanium valves or steel valves that have a black nitride coating may give different manufacturers a unique appearance but that beauty, as they say, is only skin deep. Underneath it all, is there any difference between valves?

You can't simply assume that one valve is the same as another. There is more to the equation than just good looks. Size (and weight) do matter.

While each one may only weigh ounces, in many engines there are as many as five valves per cylinder. And at an average rotational speed of 3,600 revolutions per minute, the valves of a gasoline engine open and close 30 times a second. The mass of the valves is accelerated and again decelerated with every revolution of the camshaft. This rotating mass can be significant, so smaller diameter stems are often used.

A valve with an undersized stem typically weighs about 8 to 10 percent less than one with a standard-sized stem; and a lighter valve means the engine can rev higher, pump more air and produce more horsepower. A lighter valve also means less stress on the valve springs, retainers, rocker arms, pushrods, lifters and cam lobes.

The weight of the intake valves is more of a limiting factor on the rpm potential of the engine than the exhaust valves because intake valves with their their larger head diameter are usually heavier than exhaust valves. Even a few grams less weight can make a lot of difference in an engine that's running at extremely high rpm.

Because steel generally looks like, well, steel, an understanding of basic metallurgy might be helpful to understanding the materials used to produce engine valves. There are essentially two basic types of steel used to make valves. One is "martensitic" steel and the other is "austenitic" steel. The difference is in the microstructure of the steel and how the various ingredients in the alloy interact when the molten steel is cast and cooled. This affects not only the hardness and strength of the steel, but also its corrosion resistance and magnetic properties. As a rule, martensitic steels are magnetic while austenitic steels are non-magnetic.

In martensitic steel, the steel is "quenched" (cooled) very quickly from a molten state to freeze the grain structure in a particular configuration. Under a microscope, the grain structure has a needle-like (acicular) appearance. This makes the steel very hard but also brittle. Reheating and cooling the steel (a process called "tempering") allows some of the martensite crystals to rearrange themselves into other grain structures which are not as hard or brittle. By carefully controlling the heat treatment and quenching process, the hardness and tensile strength of the steel can be fine-tuned to achieve the desired properties.

The same alloy can be used for both intake and exhaust valves (say 21-2N or 21-4N, for example), but the best results are usually obtained when different alloys are selected for the intake and exhaust valves. Why? Because an exhaust alloy that has good high temperature strength and corrosion resistance really isn't needed on the intake side, and it may not have the hardness and wear resistance of an intake alloy at lower temperatures. But while some companies sell the same alloy for both intake and exhaust valves, others offer different alloys for intake and exhaust valves.

Intake valves run cooler and are washed with fuel vapors which tend to rinse away lubrication on the valve stem. So for intake valves, wear resistance may be more important than high temperature strength or corrosion resistance if the engine will be involved in any kind of endurance racing.

Exhaust valves, on the other hand, run much hotter than intake valves and must withstand the corrosive effects of hot exhaust gases and the weakening effects of high temperatures. Consequently, a premium valve material is an absolute must on the exhaust side - especially in turbocharged and supercharged engines and those that inject nitrous oxide to boost power.

As combustion temperatures go up, valve alloys that work fine in a stock engine may not have the strength, wear or corrosion resistance to hold up in a performance application. If you want the valves to last, especially in a highly modified racing engine, upgrading to better valve alloys will be a must.

Steel alloys with a martensitic grain structure typically have a high hardness at room temperature (35 to 55 Rockwell C) after tempering, which improves strength and wear resistance. These characteristics make this type of steel a good choice for applications such as engine valves.

But as the temperature goes up, martensitic steel loses hardness and strength. Above 1,000 degrees F or so, low carbon alloy martensitic steel loses too much hardness and strength to hold up very well. For this reason, low carbon alloy martensitic steel is only used for intake valves, not exhaust valves. Intake valves are cooled by the incoming air/fuel mixture and typically run around 800 degrees to 1,000 degrees F, while exhaust valves are constantly blasted by hot exhaust gases and usually operate at 1,200 degrees to 1450 degrees F or higher.

To increase high temperature strength and corrosion resistance, various elements may be added to the steel. On some passenger car and light truck engines, the original equipment intake valves are 1541 carbon steel with manganese added to improve corrosion resistance. For higher heat applications, a 8440 alloy may be used that contains chromium to add high temperature strength. For many late model engines (and performance engines), the intake valves are made of an alloy called "Silchrome 1" (Sil 1) that contains 8.5 percent chromium.

Exhaust valves may be made from a martensitic steel with chrome and silicon alloys, or a two-piece valve with a stainless steel head and martensitic steel stem. On applications that have higher heat requirements, a stainless martensitic alloy may be used. Stainless steel alloys, as a rule, contain 10 percent or more chromium.

The most popular materials for exhaust valves, however, are austenitic stainless steel alloys such as 21-2N and 21-4N. Austenite forms when steel is heated above a certain temperature which varies depending on the alloy. For many steels, the austenitizing temperature ranges from 1,600 degrees to 1675 degrees F, which is about the temperature where hot steel goes from red to nearly white). The carbon in the steel essentially dissolves and coexists with the iron in a special state where the crystals have a face-centered cubic structure.

By adding other trace metals to the alloy such as nitrogen, nickel and manganese, the austenite can be maintained as the metal cools to create a steel that has high strength properties at elevated temperatures. Nitrogen also combines with carbon to form “carbonitrides” that add strength and hardness. Chromium is added to increase corrosion resistance. The end product is an alloy that may not be as hard at room temperature as a martensitic steel, but is much stronger at the high temperatures at which exhaust valves commonly operate.

Though austenitic stainless steel can handle high temperatures very well, the steel is softer than martensitic steel at lower temperatures and cannot be hardened by heat treating. To improve wear, a hardened wafer tip may be welded to the tip of the valve stem. Or, on some applications an austenitic stainless valve head may be welded to a martensitic stem to create a two-piece valve that has a long wearing stem and heat resistant head. The only disadvantage with a two-piece valve is that it doesn’t cool as well as a one-piece valve. The junction where the two different steels are welded together forms a barrier that slows heat transfer up the stem.

21-2N alloy has been around since the 1950s and is an austenitic stainless steel with 21 percent chromium and 2 percent nickel. It holds up well in stock exhaust valve applications and costs less than 21-4N because it contains less nickel. 21-4N is also an austenitic stainless steel with the same chromium content but contains almost twice as much nickel (3.75 percent), making it a more expensive alloy. 21-4N is usually considered to be the premium material for performance exhaust valves. 21-4N steel 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.

Unfortunately, you can’t always tell what kind of alloy a valve is made from because different valve suppliers use different alloys as well as their their own proprietary names for their valve materials. Thus one manufacturer may call their intake valve material a “422 stainless alloy” while another refers to it as an “NK-842 stainless intake material.”

Without a thorough metallurgical analysis, you can’t really compare one manufacturer’s valve material to another’s. But frankly, as long as the alloy does what it is supposed to do, does it really matter what they call it?

Performance and Heavy-Duty Valve Alloys

Materials that are commonly used for performance valve applications include carbon steel alloys, stainless steels, high-strength nickel-chromium-iron alloys and titanium. The alloys that are most commonly used for performance engines include various high chromium stainless alloys for intake valves, and 21-4N (EV8) for exhaust valves.

The brand name Inconel refers to a family of trademarked high-strength austenitic nickel-chromium-iron alloys (a "superalloy" material) that is sometimes used for exhaust valves, especially in heavy-duty engines, because of its superior high temperature strength. Inconel is a nickel base alloy that is sometimes thought of as a super-stainless steel, with 15 to 16 percent chromium and 2.4 to 3.0 percent titanium.

Inconel 751 is classified as an HEV3 alloy by SAE. This alloy has been used for the exhaust valves in some late model medium-duty and heavy-duty truck engines (to prevent premature valve erosion), but is not commonly used in performance exhaust valves. For most performance applications, the exhaust valve material of choice is 21-4N – or titanium.

Titanium is often viewed as the ultimate valve alloy material because it is about 40 percent lighter than steel, making it a good alternative for high revving engines. Lighter valves also allow more radical cam profiles that open and close the valves more quickly for better off the line performance and low end torque. The durability of titanium is similar to that of stainless steel. Titanium valves are being used in many street performance engines as well as in some production motorcycle engines.

In some cases the same alloy for both intake and exhaust valves may be used with different heat treatments. The heat treatment is very important because it determines the ultimate strength and hardness of the metal.

Titanium valves are often coated with moly or another friction-reducing surface treatment to reduce the risk of stem galling. Coated valves are recommended for street performance applications, but may not be necessary in drag racing or circle track applications where engines are torn down and inspected frequently.

Titanium valves will work with stock valve guides and seats, but for the best results they should be used with copper beryllium seats (to improve heat transfer and cooling) and manganese or silicone bronze valve guides.

A drawback to titanium may be found in the wallet – from a cost standpoint, titanium is way up there. A single titanium valve may cost upwards of $100 per valve. Even before the Wall Street meltdown, that was a lot of money for the average guy.

One way valve suppliers are taking additional weight out of intake (and exhaust) valves and competing with the high-dollar, low-weight valves today is by offering "hollow stem" valves. The valve stem is gun-drilled and micropolished to make it hollow like a pushrod. The drilling is only done in the upper 2/3 of the stem where rigidity is less of a factor than the area just above the valve head. After the stem has been drilled out, a hardened tip is welded onto the top of the stem. The result is a valve that more than 20 percent lighter than a valve with a solid stem. According to one supplier of hollow stem performance valves, these valves are good for 300 to 350 more rpm with no other modifications (same springs, rockers, pushrods, etc.).

Drilling out the valve stem to lighten the valve obviously sacrifices some strength, so a slightly stronger valve alloy may be used to maintain the same strength as before. Durability of hollow stem valves is not likely to be an issue in naturally aspirated performance engines, but hollow stem valves are not usually specified in turbocharged or supercharged engines, or in engines using nitrous oxide, because of the increased heat.

Sodium-filled hollow stem valves are available for higher heat applications, and are typically used for the exhaust valves. The sodium inside the valve stem melts and absorbs heat from the valve heat. As the valve opens and closes, the sodium sloshes up and down inside the valve to transfer heat from the valve head to the stem. This helps the head run cooler to reduce the risk of valve burning, pre-ignition and detonation. The difference in cooling is quite dramatic. With a conventional solid stem exhaust valve, 75 percent of the cooling takes place across the valve seat and 25 percent through the stem. In a sodium-filled exhaust valve, 40 percent of the cooling is through the stem so the valve can tolerate more heat.

Performance Coatings

The stems or heads of valves are often coated to enhance performance. Stock valves (as well as performance valves) usually have chrome-plated stems to protect the stem from galling when the engine is first started. Chrome-plating also helps reduce valve seal wear on engines that use positive valve seals.

Chrome has microscopic pores that retain oil, but actually creates a slightly rougher surface finish on the valve stem. Other alternatives include various thin film coatings for wear resistance and lubricity. 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.

Many Japanese OEMs use a black nitride coating on the valves instead of chrome plating. The nitride coating, which is applied in a salt bath treatment, protects the stems against scuffing and wear. Nitriding creates a thinner but harder surface layer that also does an excellent job of reducing wear.

Some performance valves may also have the stems treated with a special dry film lubricant to reduce friction and wear. With titanium valves, a dry film lubricant coating can also reduce the effects of valve erosion caused by the hot exhaust gases as they exit the combustion chamber. Dry film lubricants on the stem and inside of the valve head can also reduce the buildup of carbon deposits that can create turbulence in the incoming air/fuel mixture and exiting exhaust gases.

As for the valve face, various coatings may be used to increase heat and wear resistance in valves made of steel or Inconel. Stellite is a hard facing material that's often required for heavy-duty diesel and gasoline exhaust valve applications, and may be used in some Top Fuel applications. Stellite is a cobalt base material with a high chromium content. It is applied to the valve face to protect against oxidation and corrosion. It may also be used on the stem tip for added wear resistance.

Ceramic thermal barrier coatings may also be applied to the combustion side of the valve head to reflect heat back into the combustion chamber. The theory here is that a heat reflective coating helps the valves run cooler. This helps the exhaust valves run cooler and last longer, and reduces heat transfer from the intake valves to the incoming air/fuel mixture for a denser, more powerful mixture. Heat reflected back into the combustion chamber also improves burning efficiency and power.

Stem coatings may be plasma spray moly or a similar friction-reducing material, or a thin film coating such as diamond-like carbon (DLC), titanium nitride (TiN), or chromium nitride (CrN) applied by a physical or chemical vapor deposition process. Thin film coatings are lighter than sprayed coatings by up to 4 grams, and do not change tolerances as much. Hard thin film coatings such as diamond-like carbon are only 20 microns thick, yet are extremely durable.

One of the issues facing all aftermarket valve suppliers today – whether they make titanium valves or stainless steel valves – is the need to cover the most popular applications. This includes a growing number of aftermarket performance heads. Most of the street performance heads use the same sized valves as OEM heads, but many racing heads do not.

The head may require a valve that is slightly longer than a standard Chevy SB or BB valve, or one with a different head or stem diameter. As a result, valve suppliers now have to carry a greater variety of valve head and stem diameters, and lengths – or custom make the valves on demand.

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