Performance Engine Valve Technology: Materials and Designs

By Mike Mavrigian

Intake and exhaust valves are available today in a staggering range of choices. In this article, we attempt to clarify and explain the differences, in terms of materials, their performance aspects, an overview of valve coatings and to provide a broad reference in terms of valve selection.

STELLITE

Stellite is a hard coating applied to valve stem tips and faces to provide a hard surface, to minimize wear. Stellite alloy is a non-magnetic and non-corrosive cobalt-chromium alloy that may also contain a tungsten element. It resists embrittlement and annealing at higher temperatures. Interestingly, the term Stellite was derived from the name of a Scottish racehorse (yeah, I know…who cares?). Stellite is often applied to steel or stainless steel valves.

SODIUM-FILLED

Sodium-filled valves feature stems that are precision-gun-drilled and filled with a specially formulated sodium. This achieves weight reduction (the result of the gun-drilling to create a hollow stem) and better heat dispersion. There is some debate concerning the efficiency of this heat transfer, due to concerns that the heat transfer to the guides increases guide wear. Even with these concerns in mind, it’s interesting to note that the Chevy LS7 engine features sodium-filled exhaust valves (along with titanium intake valves).

The hollow space in the head/stem of a sodium-cooled valve is filled to about 60% of its volume with metallic sodium, which melts at about 206 degrees F. The inertia forces that result during valve opening cause the liquid sodium to migrate upwards inside the stem, transferring heat to the valve guide and subsequently to the water jacket.

HOLLOW STEM

Hollow-stem stainless steel or titanium valves (no sodium-fill) features gun-drilled stems to create hollow stems, strictly for weight reduction (this reduces valve weight by approximately 10% as compared to a comparable solid-stem valve). Citing Ferrea as an example, their hollow stem valves are gun-drilled and micropolished, and feature friction welded tips, shot-peened and rolled lock grooves, “avionics” chrome plated stems, and feature face hardness up to 42 HRc. This micropolishing reduces the risk of stress risers in the I.D. walls of the stem.

STAINLESS STEEL

Although stainless steel valves may be offered in varying grades/alloy recipes, high performance stainless steel valves are most commonly made of material referred to as EV8 (a more expensive heavy-duty stainless alloy material), and are made from a one-piece forging. In addition, some valve makers offer a stronger stainless steel formula that offers higher heat resistance. Some makers use EV8 only for their exhaust valves, while others utilize this material for both intake and exhaust valves. High quality performance stainless valves should feature hard stellite tips (since stainless is not hardenable, a hardened tip must be welded onto the stem) and hard chrome plated stems (not cheap flash chroming) to reduce guide wear. Undercut stems contribute to slight weight reduction and benefit flow characteristics. Note: if a particular brand of stainless steel valves does not feature a hard tip, the use of lash caps will be required.

TITANIUM

Titanium (chemical symbol Ti) offers the highest strength-to-weight ratio of any known metal. In an un-alloyed condition, Ti is as strong as some steel materials but about 45% lighter. When used to manufacture automotive valves, titanium is alloyed with small percentages of various materials, including copper and molybdenum. Titanium is a fairly hard material and can be challenging to machine, as it can gall if tooling isn't hard and sharp enough, and if the material isn't cooled properly during machining.

Just for the sake of trivia info, titanium was actually discovered independently by a couple of guys including a British amateur geologist and a German chemist in the late 1700s. The German, Martin Heinrich Klaproth, reportedly named the material titanium for the Titans of Greek mythology. Pretty cool. Maybe this dude was a racer at heart without even knowing it. Eventually, starting in the 1950s, titanium began to see serious use by both the U.S. and the Soviet Union for military applications including submarines and jet aircraft.

Many titanium valves are generally produced by starting with a forging, then machined to final shape, but some are produced using a two-piece inertia-welded design to attach a partially machined valve head and stem together. During this process, the two previously machined parts are fused together using state-of-the-art equipment that uses inertia and a force to weld the two pieces into one solid component. Once the valve blank is welded, it's heat treated to alter the grain structure of the titanium through precision heating and cooling at varying temperatures, taking into account the properties of the alloys and the specific application (intake or exhaust). This process is so effective that inertia welded valves have been certified as having a superior grain structure as compared to a one-piece forged design. The valve is then CNC machined and in many cases undercut in the stem area to allow a bed for the inlay of a coating. The valve is then plasma moly coated. Specific sections of the valve are further machined and the stem is ground, leaving the plasma moly coating over only the desired stem area. The head, stem and keeper grooves are then final machined. Stem grinding is then finalized to establish dimensional tolerance to within 0.0002". The valve is then precision polished to reduce the potential for carbon buildup.

Various styles of valve tips are generally available, which includes a hardened steel tip, a diamond-like coating or a ceramic-coated tip (ceramic tips are to be used in conjunction with lash caps) and thin-film technology such as a PVD coating.

As we noted earlier, titanium is a relatively soft material, requiring a protective contact surface at the stem tips, usually requiring hardened lash caps. When valves feature stem diameters smaller than 5/16" (7mm or less in diameter), a specialized hard coating is applied to the stem tip in order to protect the tip from lash cap friction.

The ceramic coating is a durable hard coating intended to protect the titanium from the friction caused by the lash cap. Other coatings such as a PVD (plasma vapor deposition) treatment, a CrN (chrome nitride) treatment, CVD (chemical vapor deposition) or DLC (diamond-like carbon) or other highly specialized protective applications may be applied to the tips. This hardened feature at the tip prevents material transfer or galling between the tip and lash cap.

Hollow titanium valves are also available, either with hollow stems or with a combination of hollow stems and hollow heads. Hollow stem designs reduce valve weight by about 10%. The hollow head design is a proprietary process that removes an additional 6 to 8 grams of weight (of course, depending on valve size). As part of the proprietary process, the inside of the valve head may be reinforced to provide a support structure for strength and rigidity.

When a stem is gundrilled, careful attention is paid to achieving a consistent precision surface finish and concentricity in the I.D. to obtain uniform stem wall thickness. Sonic measurement technology (and other proprietary methods) are employed to monitor the I.D. operations.

The commonly used lock design for titanium valves is the "super 7" style, commonly referred to as a 7-degree lock, which is actually closer to 8 degrees. Lock grooves are square grooved or radiused for superior lock engagement as well as reduced potential for stress risers. Some valve manufacturers apply a specialized thin-film PVD coating to the locks and retainers to prevent material galling between titanium/titanium materials. The lock-to-retainer interface is perhaps the biggest galling-potential issue that must be addressed.

While undercutting is employed on many titanium valve designs, there are occasions where exhaust valves may feature an overcut in order to provide the required additional cross-sectional mass needed for some extreme applications.

Precautions concerning the handling and use of titanium valves

• Do not touch the valve surface with your bare hands, since fingerprint acids may affect the coating). Use gloves or coat the valve with oil before handling.

• Never use a lapping compound, or any abrasive material when the valve is coated with a PVD style coating.

• Valve seats should be replaced during each and every rebuild in order to insure a proper valve-to-seat contact. The width of the contact zone (valve face to valve seat) should be at least 1mm.

• New valve seats should be a relatively soft material, such as bronze or nodular iron (heat treated to Rockwell RC32 or less).

• Unless directed otherwise by the valve maker, always use hardened lash caps on titanium valves. Some makers offer valves built with friction-welded hardened tips. Bare, unprotected titanium tips are relatively soft and will mushroom when exposed to rocker arm forces.

If a titanium valve features a stellite tip (hardened stellite tipped valves don't require lash caps), during valve service, the stellite tips can be ground, but with caution. You should be able to safely remove approximately a maximum of 0.015" to 0.020". It is absolutely essential that you check with the valve maker to determine if the tip is hardened or not, and if hard lash caps are required or not! Don't assume anything…. If you run without lash caps when they're required, you'll ruin the valves in a heartbeat.

As far as valve seats are concerned, again keep in mind that titanium is a relatively soft material. A traditional cast or hard seat can beat a groove into the valve face, so a nickel bronze seat material is recommended.

Titanium valves are extremely lightweight and are designed for applications where valvetrain weight needs to be reduced, for high-rpm and extended high-rpm applications, since titanium valves allow for higher engine speeds and will accommodate highly-aggressive camshaft profiles. The lighter weight contributes to minimized wear on rocker arms and improved valve spring life. As valve weight is reduced, lighter springs can be used. As spring force is reduced, this reduces frictional loads between the lifters and cam lobes. So, the use of titanium valves offer both higher engines speeds, quicker engine acceleration, and reduced friction throughout the valvetrain. While lighter weight and the resulting ability to achieve higher engine speed is of obvious benefit in any form of racing, the ability of the engine to produce quicker acceleration is extremely beneficial in a drag racing application.

It should be obvious that titanium valves are designed for higher engine speeds, which is fine for higher top-end power. However, for extreme temperature situations (blown, turbo, nitro engines), titanium may not be the ideal choice. Also, for many street applications, titanium may not be a good choice for an engine that doesn't need to rev as highly, and for an engine that will be buttoned up and not torn down and serviced regularly. In other words, it's probably best to reserve the use of titanium for naturally-aspirated race or inlet-side forced induction applications where valvetrain weight and sustained high-rpm use is paramount.

The benefits of lighter valves can be summed up accordingly: Creating a broad power band of lower-RPM power for the run off-the-corner has the greatest impact on lap times, and represents the largest challenge to engine builders.

However, whether the goal is maximum peak power or the broadest possible torque curve, titanium valves and other lightweight valve train components give the engine builder greater freedom in choosing camshaft profiles. The lighter mass also promotes faster valve acceleration from any RPM, again giving the engine builder and cam designer more flexibility. The additional benefits of lighter valves, retainers and locks is that they can push valve float to levels of RPM above which you intend to operate the engine.

NIMONIC 90

Nimonic is a nickel-chromium alloy. A specific grade of this material, Nimonic 90, is used by some makers for producing high performance valves. Nimonic 90 is a "super" alloy comprised of nickel-chromium-cobalt, which offers high strength and especially an ability to withstand extremely high temperatures, reportedly well within the 2000 degree F range, without distortion. This material is also widely used in aerospace industries for applications such as valves in turbo motors and blades and discs in gas turbines. Success has been noted by the aftermarket industry in such extreme applications as nitromethane and high-boost turbo applications such as multiple-turbo tractor-pull engines.

INCONEL

Inconel is a registered trademark of Special Metals Corporation, referring to a family of nickel-based superalloys. Inconel alloys are oxidation and corrosion resistant materials designed for use in high heat environments. Inconel retains strength over a wide temperature range. As opposed to steel or aluminum, Inconel doesn't creep as much (change dimension) under high heat use. Inconel is commonly used in high stress aircraft applications such as high-speed airframe and jet engine components.

Five "grades" of Inconel are in common use, including 600, 625, 690, 718 and 939. As an interesting sidenote, a special Inconel X material was used in the makeup of the skin for the legendary X-15 rocket plane.

Basically, the benefits of Inconel include light weight, extreme resistance to temperature, high strength and resistance to thermal dynamics.

Inconel alloy makeup (depending on the specific alloy mix) can include carbon, manganese, silicon, phosphorous, sulfer, nickel, cobalt, chromium, iron, aluminum, molybdenum, titanium, boron and copper, with the heaviest material concentration accounted for with nickel and chromium.

Inconel valves offer extremely high thermal resistance and are designed for high heat applications as found in turbocharged, supercharged and nitrous applications.

Reducing Valve Mass: A Camshaft Maker's Point Of View

Since valve weight in particular naturally relates to valve spring force and cam profile selection for given race applications, I contacted the folks at Comp Cams for their input.

For the majority of street engines, a quality stainless steel valve is recommended. Although some engine builders prefer titanium valves for most race applications, other builders that specialize in turbocharged applications prefer a high nickel Inconel valve.

Hollow stem valves tend to work great on the intake side, but they are much more difficult to manufacture and to inspect for defects on the I.D. surface. Many of the upper-echelon engine builders shy away from hollow valves for that reason in endurance (NASCAR or 24-hour style) racing.

Stainless steel valves are most common in street and mild-performance racing. Titanium is used when valve weight is important and when budget is not a consideration. Inconel is used when exhaust gas temps get really high. Stainless steel (for street performance) has much better durability characteristics than titanium, and the street guys won't usually see the real benefits of titanium. In racing, use titanium when you want to lose weight and spend a lot of money. Of durability is a concern, and you're already making as much power as you want and are already turning the engine as high as you want, then you need to use a stainless steel material. If you're running nitromethane, then an inconel exhaust valve material will be your best bet if you want to finish a race. NASCAR engines use a variety of titanium materials because of the temperature and impact related issues associated with their severe applications.

For the exhaust, sodium-filling is the best way to increase the head capacity of a hollow exhaust valve. If stock diameter steel valves are required, but a valve weight is not mandated, using a hollow intake and sodium-filled exhaust is an advantage.

The most critical point is to get mass out of the valve. The lighter the valve, the stiffer the valvetrain is in relation to the mass it must move. Also, as the valve mass is decreased, the spring force needed to control a given valve motion can be reduced and/or a more aggressive cam design utilized that can make more power

To prevent excessive tip wear on titanium valves (especially the small O.D. non-hardened tip variety), using a lash cap provides an excellent wear surface for the roller tip, sliding contact or cam follower. While you always want the rocker to push down on the section of the cap directly over the stem, using a lash cap certainly gives you a better sense of safety as you approach the edge of the valve in high lift applications with a very small (5 to 7mm) stem.

Because engine builders and cam designers push limits, the stems get smaller and the lift gets higher. As a result, lash caps are used with smaller valves to better distribute the load across a larger area than the base stem tip area. They are also used with higher lift because when the lift is increased, the rocker arm sweep length usually increases across the valve or lash cap as well, compounding the issues caused by the smaller valve stem diameter.

The question becomes, "Where is the safest and best way to invest my money when building this engine for this specific application and within this budget?" Sometimes, your answer will be a hollow valve, but in most cases it would probably be a solid valve stem unless we see a major technical jump on the manufacturing side. As the OEMs start pursuing that route on the mass market side, we could find new technologies available to make these parts on the performance and racing side. We have certainly seen that effect with the availability of several new beehive-style valve springs and now nitrided flat tappet cams that we offer. Just a few years ago, we could not provide either of those technologies dependably, at a high level, and for a reasonable cost, but lower machine cost (although the cheapest machine was still on the order of a quarter-million dollars plus) for the tools to manufacture these parts became available in recent years.

Solid stems are stronger; hollow stems are lighter. However, the quality control of an inside stem surface is very difficult to control. Because of the pounding of the valve upon closing, the sensitivity to failure is compounded if there are machining marks that can neither be controlled nor removed because they cannot be seen.

While 95% of our market uses a square groove lock, the stresses in the valve are minimized with a single round groove. The lowest stress system is a top lock design with a small round groove at the top of the lock, and the lock is designed with a slightly smaller angle than the retainer so that the valve is held by the collet force squeezing more at the bottom region of the lock-to-valve interface.

Round grooves are best because they address the issue of stress concentration zones associated with a very small radius of the inside corner of a square groove lock. In high-end racing with any material valves, retainers and locks, it is best to use only a single groove because it forces the lock to grip the valve stem and hold it in place. Many OEM engines feature multiple-groove steel locks and valves that allow the valve to spin in the locks, which is fine for street and low-end performance. Because there is a loose fit between the valve and locks, it could cause an over-stress condition if used in severe racing.

The Bottom Line

As a quick summary, high quality EV8 stainless steel valves are a good choice for street and naturally-aspirated race engines, while titanium valves accommodate high engine speeds in race engines that don't experience uncommon extremes in temperatures, and Inconel (and other similar nickel content) valves are suggested for extreme cylinder pressure/extreme temperature applications (primarily exhaust). For extreme-temperature applications such as very high cylinder pressure nitromethane, blown or supercharged use, a combination of titanium intake valves and Inconel or Nimonic exhaust valves are appropriate.

Valve Coatings: More Than Meets The Eye

Instead of simply listing the names for the various valve coatings, the following list provides extra information about each of these specialized coatings.

• PVD (Physical Vapor Deposition) occurs because of a physical reaction. Inside a vacuum chamber plasma environment, metals are deposited via evaporation, sputtering or arcing fragments of the metals which are physically moved on to the substrate. In other words, there is no chemical reaction which forms the coating on the substrate.

• CVD (Chemical Vapor Deposition) occurs because of a chemical reaction. The process exploits the creation of solid materials directly from chemical reactions in gas and/or liquid compositions or with the substrate material. The product of that reaction is a coating material which condenses on all surfaces of the part to be coated and inside the vacuum chamber plasma environment.

• DLC (Diamond Like Carbon) coating is a thin-film coating applied via a plasma-assisted Chemical Vapor Deposition (PaCVD) process. This coating combines very low frictional resistance and extreme hardness. The coatings are used to reduce wear and friction for rapidly-reciprocating components, where friction reduction is a primary goal. Common applications include finger followers, tappets and piston pins.

• CrN (Chromium Nitride) is a thin-film coating also applied using a PVD process. According to Del West, a cathodic arc is discharged at the target to evaporate the chromium into a highly ionized vapor, which is done in a partial pressure of nitrogen. This provides a higher level of adhesion as opposed to a PVD sputtering method in which a glow plasma discharge bombards the material and sputters some material away as a vapor. Del West commonly uses this process for titanium, steel and nickel-based valves.

Thermally-sprayed coatings can provide thick coatings over a large area at high deposition rate as compared to other coating processes such as PVD or PaCVD. These are coatings that include plasma spraying and High Velocity Oxygen Fuel (HVOF) spraying that are widely used to protect valve stems and tips.

Thin-film coating options such as CrN (Chrome Nitride), TiAlCrN (Titanium Aluminum Chrome Nitride), DLC (Diamond-Like Carbon) and a:SiC (Amorphous Silicon Carbide) are selected during the valve design process based on the suitability of the coating properties for the specific engine application and with reference to historical post-engine teardown feedback and analysis.

In certain applications, a combination of coatings may be selected for an individual valve.

For example, the “ductile” properties of a CrN coating (Hardness 1,600 HV) will be selected for application to the valve tip, while the “low friction” attributes of a DLC or a:SiC coating (Friction coefficients 0.1 or less) will be chosen for application to the critical valve seat head region.

Dry fuels such as those with low-sulphur content or alcohol based are suitable environments for certain low-friction and inert thin-film coatings. The application of a coating upon the valve head and valve stem can be exploited as a “solid lubricant” minimizing adhesive wear between the valve-seat or valve-guide interface. Adhesive wear, also known as scoring, galling, or worse case seizing, results when two solid surfaces slide over one another under pressure. Surface projections, or asperities, plastically deform and eventually weld together under the high localized pressure. As sliding continues, these bonds break. This creates cavities on one surface and projections on the other. Tiny abrasive particles can also form causing additional wear.

Specific to applications associated with excessive exhaust gas temperature, hybrid coatings (Pt, Pd, Nb based) have been examined as a means to retard embrittlement of the base Ti material by minimizing the ingress of oxygen through the coating and represent novel strategies to yield robust coatings for ultra-high temperature environment applications.