VALVE SPRINGS

Materials history and physical concepts

BY **FERNANDO CURELLO**

Let's begin by talking about basic concepts of one of the most important and highly stressed components in the internal combustion engine, valve springs! Especially when high mileage heavy duty engines, high performance or pure racing engines are the final users…

A valve spring is a helical compression spring, and its main job is to provide forces to the intake and exhaust valves to seal the combustion chamber. At the same time, its function is to provide enough forces (closing loads) to the valves by avoiding opening under high pressures, or by bouncing at the closing phase. It really is a component that absorbs energy while being compressed, and returns that energy to the valvetrain by putting forces on it.

One way to think about it is a music concert that has an orchestra directed by the camshaft. The camshaft "orders" the valves to open, accelerate, decelerate, and close, then the "musicians" called tappets, pushrods, rocker arms, springs, and valves, must avoid physical separation under maximum negative accelerations that could lead to lost control and valve bouncing.

We must consider that all the "musicians", in addition to the spring itself, have their own elasticity, which means that they suffer deformations under the loads that compress them. When unloaded, they return those forces to the system, creating vibration waves that must be carefully considered when designing their shapes, weights, structure, materials, elastic limits, etc.

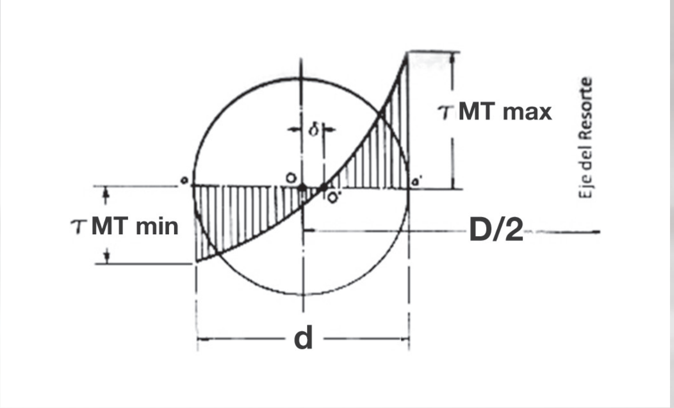


Figure 1: Distribution of torsion stresses in a coiled round wire valve spring.

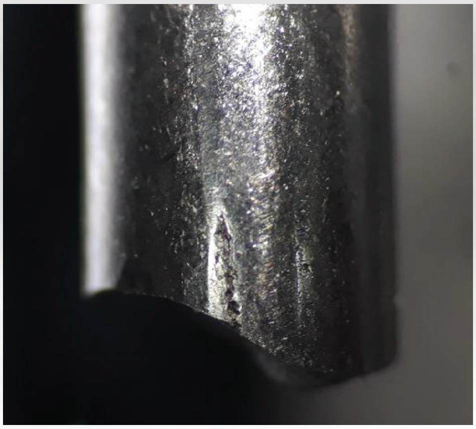
Figure 2: Broken valve spring.

When you think about it, all this mess happens multiple times per second, especially in a race engine. The valvetrain must withstand millions of opening and closing cycles without failures and withstand temperatures around 260°F or sometimes more. We begin understanding why the valve spring's job is anything but a relaxed and easy one.

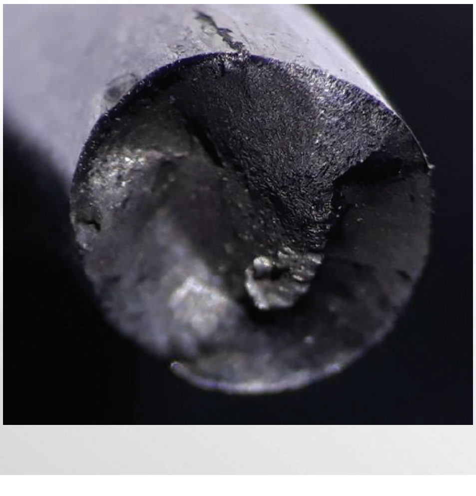
At 6,000 rpm, a spring is loaded and unloaded 50 times per second! A NASCAR race engine that runs at 9,000 rpm is opening and closing springs 75 times per second, and race bikes running at 15,000-16,000 rpm at the unbelievable rate of 125-133 times per second! For now, this is the limit for the valve springs as we know them; beyond this, they can't work and pneumatic controls are required, like in Moto GP and Formula 1 engines. For Formula 1, the regulations before the 2006 season allowed over 19,000 rpm. Some said that reached 20,000 rpm in some races! Can you imagine the springs being loaded and unloaded at more than 166 times per second?

The valve spring manufacturing, design, development and mainly the valve spring materials have toured an outstanding and marvelous road. In fact, one of the biggest "breakthroughs" in valve spring development was a process called "Super Clean" or SC alloys. This is a manufacturing process that was first developed by a Japanese manufacturer (Kobe Steel) in the early '80s. This process allowed for a very low quantity of harmful non-metallic inclusions below the surface of the steel wires. Inclusions were the reason for most of the valve spring fatigue failures before the '90s… This improved process pushed the fatigue limits of these spring materials much higher than years before.

How does inclusion translate to failure? When we describe the loading and unloading process for a valve spring, when compressed, the steel wire is in fact twisted, therefore stressed as torsion. The maximum stress at the surface of the wire, and the higher value at the internal diameter of the coiled spring (MT max) there could be also some tensile stresses due to bending, because as the loads are coaxial (along the spring axis), and if the spring is long enough could flex, or even worst, buckling if the length-OD relationship is too big.



Figures 3 and 4: Broken wire surface defect and cross section.



Please refer to Figure 1, where "d" is the round wire diameter, and D is the diameter of the centerline of this coiled round wire.

As you can see, the stress is not zero at the center of the wire cross section, as in any torsional straight bar. That is due to the spring curvature that having a bigger radius at the outside (OD) than in the inside (ID), the stress is higher in the inside than at the outside, and not zero at the center. In the stress calculations, this effect is taken in consideration through a coefficient called the Wahl factor which considers the relationship between the spring mean diameter to the ID.

When microscopic inclusions are present below the surface, microcracks are generated within the cycling process of loading-unloading (a fatigue behavior that we will explain later). The cracks grow and could finally end in a macroscopic material breakage, as shown in Figure 2. In Figures 3 and 4, we can see a magnified view of the broken wire surface and cross section showing the surface defect that generated the so-called fatigue failure. The micrograph shown in Figure 5 (on the following page) obtained through an electronic microscope (EDS system) demonstrates that the surface defect had also a subsurface inclusion of not more than 10 microns (.00040"), that generated the fatigue failure after several thousand cycles.

Reducing the size and quantity of said non-metallic inclusions, the material can withstand higher stresses, more cycles, allow for higher loads, more durability, and a greater fatigue life. Nowadays, 100% of the valve spring alloys are of the Super Clean (SC) class.

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Let’s dive into the technical aspects and some history of the valve spring alloys. From the early days of the internal combustion engine, valve springs were manufactured from hard drawn wires of high carbon steel, similar to “piano wire” or “music wire”. Their tensile strengths were initially in the 1,300-1,400 MPa (188,000-203,000 PSI) range (for a wire diameter of .200", because the tensile strength values change with the wire size). Their “names”, according to the American Standard of Testing Materials, were ASTM A227, A228 and ASTM A229 (equivalent to the Society of American Engineers, SAE 1060 and 1070).

They were first manufactured in Austria and Sweden and had a very high-quality steel manufacturing process. In 1941, a Japanese manufacturer called Kobe Steel began making piano wires, the KRS steels that were first used for aircraft valve springs and later automotive applications. Please refer to the Valve Spring Steel Chart in Figure 6, on page 62.

After the war, the oil quenched and tempered (OT) process was successfully implemented in the USA. By the mid ’60s, an American facility began producing high quality spring wires that grew to become one of the biggest spring wire mills in the world – ASW (American Steel Wire Corp.) – improving the hardness and the tensile strength to approximately 1,500-1,600 MPa (217,000-232,000 PSI), like the popular SAE 1070, but now oil quenched and tempered (OT) to the equivalent automotive application ASTM A230 or ASSOCIATED SPRING AS 25. The Swedish steel mill company Garphyttan (OTEVA 31) and the Japanese Kobe Steel (KPR steels) were producing all these the “must-use” valve spring steels wires for many years around the world.

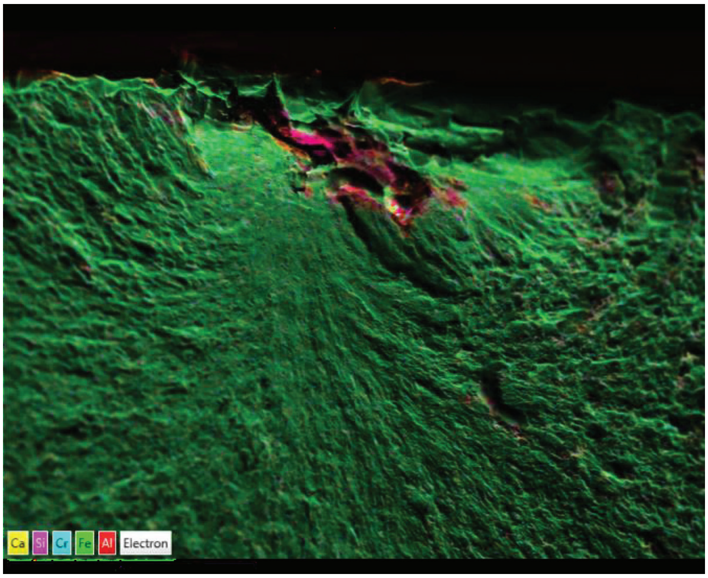

Figure 5: Microscopic inclusion below wire surface.

The race to improve the mechanical characteristics followed, adding Chrome and Vanadium to the alloys, and steels like the SAE 6150 (ASTM A231/A232), AS 32 from Associated Springs, OTEVA 60 from Garphyttan, or the SWOSV-V from Kobe Steels, reached approximately 1,700-1,800 MPa (246-261,000 PSI) tensile strength, enabling the design and development of lighter and

Figure 6

VALVE SPRING STEEL GRADES	C %	Si %	Mn %	Cr %	V %	Ni %	Mo %	W %
MUSIC OR PIANO WIRE ALLOYS								
OLD MUSIC WIRE STEEL ALLOYS	0.85	0.19	0.60					
PIANO WIRE ASTM A227 CLASS I (APPROX. SAE 1050)	0.50	0.25	0.80					
PIANO WIRE ASTM A227 CLASS II (APPROX. SAE 1060)	0.65	0.25	0.80					
PIANO WIRE ASTM A228 (APPROX. SAE 1070-1090)	0.85	0.20	0.40					
PIANO WIRE ASTM A229 (SIMILAR TO SAE 1070)	0.70	0.23	0.75					
PIANO WIRE KOBE STEEL KRS 62A®	0.62	0.22	0.50					
PIANO WIRE KOBE STEEL KRS 72A®	0.72	0.22	0.50					
PIANO WIRE KOBE STEEL KRS 82A®	0.82	0.22	0.50					
OIL TEMPERED HIGH CARBON STEEL ALLOYS, APPROX ASTM A 230								
ASSOCIATED SPRINGS AS 25®	0.70	0.22	0.80					
GARPHYTTAN OTEVA 31®	0.67	0.22	0.70					
KOBE STEEL KPR 92AC®	0.92	0.20	0.50					
KOBE STEEL KPR 100 A®	1.00	0.20	0.50					
AMERICAN STEEL WIRE CORP. ASW (ACCORDING TO ASTM A230)	0.67	0.25	0.80					
CHROME-VANADIUM OIL TEMPERED STEEL ALLOYS								
ASTM A231/A232 (EQUIVALENT TO SAE 6150)	0.50	0.27	0.80	0.95	0.19			
ASSOCIATED SPRINGS AS 32®	0.50	0.27	0.80	0.95	0.20			
GARPHYTTAN OTEVA 60®	0.67	0.22	0.70	0.50	0.10			
KOBE STEEL ACCORDING TO JIS SWOSV-V	0.50	0.25	0.80	0.90	0.20			
AMERICAN STEEL WIRE CORP. ASW (APPROX. ASTM A232)	0.68	0.22	0.70	0.50	0.17			
CHROME-SILICON OIL TEMPERED STEEL ALLOYS								
ASTM A877 (EQUIVALENT TO SAE 9254)	0.55	1.40	0.70	0.65				
ASSOCIATED SPRINGS AS 33®	0.55	1.40	0.65	0.65				
AMERICAN SPRING WIRE ASW 9BV®	0.55	1.42	0.67	0.65				
SUZUKI GARPHYTTAN OTEVA 70®	0.55	1.40	0.65	0.65				
SUZUKI GARPHYTTAN OTEVA 74®	0.65	1.47	0.70	0.67				
KOBE STEEL HRS6® (APPROX. JIS SWOSC-V)	0.55	1.45	0.75	0.75				
CHROME-SILICON VANADIUM OIL TEMPERED STEEL ALLOYS ASTM A877B								
AMERICAN SPRING WIRE ASW 9MV®	0.64	1.45	0.65	0.70	0.11			
SUZUKI-GARPHYTTAN OTEVA 75®	0.60	1.42	0.65	0.75	0.125			
ASSOCIATED SPRINGS WIRE AS 50®	0.60	1.42	0.65	0.75	0.125			
KOBE STEEL ALLOY KHV7® (ACCORDING TO SWOSC-VHV)	0.62	1.45	0.75	0.60	0.13			
CHROME-SILICON-VANADIUM STEELS FOR NITRIDING								
ASW.PENGG 90 VN®	0.58	1.95	0.85	0.95	0.10	0.30		
SUZUKI-GARPHYTTAN OTEVA 76®	0.60	1.47	0.70	0.75	0.15	0.30		
SUZUKI-GARPHYTTAN OTEVA 90®	0.60	2.00	0.85	0.95	0.10	0.30		
KOBE STEEL KHV 6N®	0.60	1.45	0.65	0.90	0.08	0.35		
KOBE STEEL KHV 10N®	0.58	2.00	0.85	0.95	0.10	0.30		
KOBE STEEL KHV 12N®	0.60	2.15	0.45	1.75	0.27	0.20		
CHROME-SILICON-VANADIUM + MOLIBDENUM AND TUNGSTEN								
SUZUKI-GARPHYTTAN OTEVA 91®	0.63	2.00	0.45	0.90	0.10	–	0.10	
SUZUKI-GARPHYTTAN OTEVA 96®	0.65	2.15	0.45	0.97	0.13	–	0.13	
SUZUKI-GARPHYTTAN OTEVA 101®	0.60	2.25	0.50	1.25	0.15	–	0.15	0.15

shorter valve springs, withstanding the higher engine temperatures and stresses, and raising the fatigue limit, which means better durability under increasing rpms and cam lifts.

By the mid ’60s, two elements were added to further improve the heat resistance and fatigue limits, as well as hardness and tensile strength. Silicon and Chrome, now known as the Chrome-Silicon oil tempered alloys, like the ASTM-A877 (SAE 9254), AS 33 from Associated Springs, or the ASW 9BV, that reached the 1,830-1,930 MPa (265,000-280,000 PSI) tensile strength values and became the standards for the automotive valve springs.

In years to follow, spring wire manufacturers from Japan like Kobe Steel, and the Swedish Garphyttan refined the Cr-Si alloys, releasing the Kobe Steel HRS6 and Garphyttan OTEVA 70, OTEVA 74.

These Chrome-Silicon alloys led the way and were how valve spring wire manufacturers worldwide were measured. Currently they are widely used for different applications, ranging from OEM to racing engines.

With the environmental emissions regulations and pressure for better fuel economy, lighter valvetrains were needed as engines had to run at higher rpm. Better and special alloys had to be developed, because the higher cycling of loading-unloading for the valve springs produced accelerated fatigue breakages.

To merely raise the tensile strength was not further possible over the 1900 MPa, the manufacturing process had to be improved on techniques for reducing surface scratches and decarburized layers, both of which can adversely affect the fatigue strength of oil-tempered wires. So, a method for peeling the wire rod surface over the whole length was successfully developed by the Japanese manufacturers known as “shaving”; this process uses a shaving die that peels away the surface layer of the steel wire. It leaves a hardened surface that requires a subsequent annealing heat treatment process to allow the wire to be drawn to the finish size.

Another method that was successfully developed in the USA, was the surface grinding, patented by ASW, that used a rotary grinding method and eliminated the need of additional annealing.

Other techniques that the spring manufacturers worked hard to improve were the stress relief heat treatment after coiling (usually below 400ºC), and the well-known shot peening process that induces compressive (negative) stresses on the spring surface, counteracting the residual tensile (positive) stresses occurred due to coiling.

When the wire is coiled to a compression spring the material at the inside diameter (ID) of the spring is upset and shortens by plastic deformation. The material on the outside diameter of the spring (OD) is subjected to tensile stress and extends. These changes to the shape cause residual tensile stresses at the inside of the spring which diminish the resulting fatigue strength. With the shot peening process, considerable improvement in both fatigue strength and surface compressive residual stresses could be obtained.

Nowadays, the shot peening procedures are performed not only once but maybe two or three times along the spring manufacturing process, after the coiling, reducing the sizes of the steel beads. Normal shot peening usually begins with steel beads of mean diameter of .60mm to .80mm (.0236" to .0315") from cut steel wires, and depending on the type and usage of the spring, could be followed by other steps with smaller steel beads, like 0.20mm (.008"), 0.10mm (.004") or even less than .05mm (.002").

The effect of shot peening on valve springs is firstly to prevent fatigue fracture from surface defects, and secondly to delay or stop the micro crack that could have progressed to the surface from a sub-surface harmful inclusion.

When we mention sub-surface nonmetallic inclusions, Kobe Steel developed the Super Clean process, as mentioned above, and new standards for the same alloys, but now SC (Super Clean) was developed to control the maximum size and quantity of sub-surface nonmetallic inclusions, for instance not more than 15 microns (.0006") up to 1mm (.040") below the surface, and allowing certain quantities if they are between 10 to 15 microns (.0004" to .0006") deep, or between 5 to 10 microns (.0002" to .0004") deep.

Another important procedure that it is of paramount importance is the hot presetting to reduce spring relaxation. This is the effect of spring shortening after several thousand cycles, due to a combination of working temperatures and the loading-unloading effect. After coiling and shot peening, the springs are preloaded and installed in a continuous furnace at 300-390ºF (150-200ºC) for 10-20 minutes. This way, the spring enters in relaxation, shortening and losing height, to reach the final desired free length. There will not be another relaxation when loaded and subjected to the same conditions, already installed in the cylinder head and the running engine.

New developments that took place in the wire valve spring world included the addition of Vanadium to the Chrome Silicon alloys, becoming the Chrome-Silicon-Vanadium alloys. Vanadium was found to be an austenite grain size refiner, and so can contribute to improve resistance to the spring relaxation mentioned before. (Austenite is a microscopic constituent in steels, formed as a solid solution of Carbon in Iron. It is found in the Iron-Carbon alloys when heated over a specific temperature depending on the type of steel, usually around 1330-1350ºF.)

Alloys like the Garphyttan OTEVA 75, the American Steel Wire ASW alloy 9MV, or Associated Springs AS50, and Kobe Steels KHV, raised the tensile strength limits to the 1,900-2,000 Mpa (275,000-290,000 PSI) and accordingly the fatigue resistance.

Lately, the addition of Nickel to those alloys, enabling the application of carbonitriding techniques to the wires further extended the fatigue limits, like the OTEVA 90 or the similar ASW.Pengg alloy 90 VN or Kobe Steel alloys KHVN that must be gas nitrided to obtain the maximum fatigue and relaxation properties possible, reached 2000-2100 MPa (290,000-304,000 PSI) for tensile strength in 5mm (.20") diameter wire.

Recently, new Suzuki-Garphyttan alloys named OTEVA 91 and OTEVA 96 included Molybdenum to further increase the mechanical properties, and most recently another element added to these alloys has been Tungsten, releasing OTEVA 101 as the top of the Suzuki-Garphyttan valve spring steel wire line. Tensile strength of these alloys is today in the range of 2100-2200 MPa (305,000-319,000 PSI), enabling high stressed valve springs with smaller and lighter designs than ever before.

As you have read, these big companies have gone through several joint ventures through the years, like Suzuki Metal Industry Company and Garphyttan, forming Suzuki Garphyttan in the ’80s, today owned by another giant in the steel world like Nippon Steel, and American Spring Wire Corp. with Pengg AG of Austria, forming ASW.Pengg LLC.

But there was another important requirement for the engines that also pushed the valve spring designs to move forward, like the need for smaller cylinder heights to reduce weight and lower engine heights in the vehicles. Then, non-round wires appeared on scene, like the elliptical wires, ovate (or egg shaped) wires. This process coiled the spring with the smaller diameter of the oval along the spring axis, the overall length or free length could be shortened, reducing valve lengths and installed heights. Please refer to Figures 7 and 8 (see page 68) for such ovate designs.

Here we can share an interesting story… The ovate or egg-shaped cross section valve spring wire was invented by in 1959 by Professor H.O. Fuchs, a German Mechanical Engineer, Emeritus Professor at Stanford University in California. At that time, there were neither computerized stress analyzing methods, nor manufacturing processes to develop these wires. A theoretical controversy took place for many years about the practical advantages of this invention. Since 1983, with the development of the Finite Element Analysis, computer capabilities and CNC programmable manufacturing capabilities, these new wire shapes could be developed and calculated.

There are also other important advantages with the ovate or elliptical wires. One is that as the highest stress at coiling always occurs at the inner diameter of the coiled spring (ID), due to the ovate shape this stress is reduced and moves from the inner

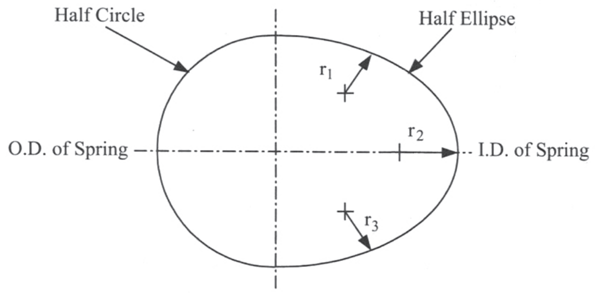

Figure 7: Conceptual ovate wire design.

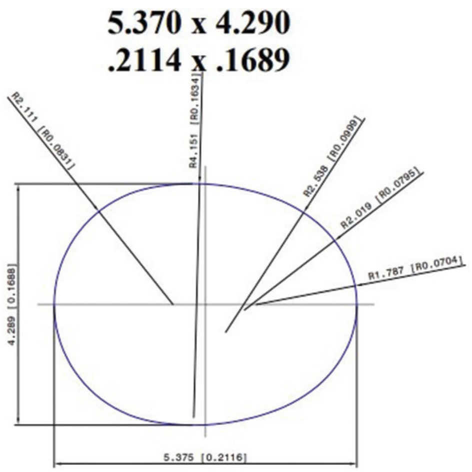

Figure 8: Example of ovate spring wire cross section.

diameter, that way levels the stress values with the OD, reducing the maximum stress inside and improving the fatigue life.

Another and not minor advantage is that being a shorter spring than a round wire spring with the same loads, it is lighter and so its natural frequency is higher, enabling the engine to run at higher rpm, moving the resonance risk upper on the rpm range. We will explain all the dynamics involved in the valvetrain, with its natural frequencies and resonance factors in my next article.■

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The author sincerely thanks the RASA springs factory for their help with many of the pictures and diagrams shown in this article, and their invaluable comments about the valve spring history, since they have been in business manufacturing springs for the last 61 years.