Hermetic Seals

Summary

The hermetic seal functions to prevent the passage of liquid, gas, and particulate, either into a protective vessel, or out of a protective vessel.

The goal of a hermetic seal is to protect something inside a hermetic vessel from the environment around it, or to protect the environment from the contents of the vessel.

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The term, "hermetic seal" is derived from the Greek god, Hermes, who is credited with making the first sealed glass tube. Subsequently, sealed vessels have been referred to as hermetic or non-hermetic based on the performance of their seal.

Hermetic seals are used widely for food packaging, medical, electronic, MEMS, sensor, and aerospace applications.[1] Primarily, the hermetic seal functions to prevent the passage of liquid, gas, and particulate, either into a protective vessel, or out of a protective vessel.

The goal of a hermetic seal is to protect something inside a hermetic vessel from the environment around it, or to protect the environment from the contents of the vessel. Sometimes, a hermetic barrier is a simple wall construction, but, in other cases, an application may require a "feed-through" feature, like electrical wires that need to be connected from an external device to a device inside a hermetic package. [2]

For feed-through features, material compatibility, coefficient of thermal expansion (CTE), and mechanical strength must be factored into the design. For example it is common to make feed-through electrical connections by embedding platinum wires in a ceramic wall because the CTEs of these materials are well-matched.[3]

It is convenient to discuss hermetic systems in terms of a penetrating species and a barrier. In a perfect hermetic system, the penetrating species absolutely cannot pass through the hermetic barrier under specified conditions. Generally, a hermetic seal is implemented because it is desirable to protecting something on one side of the barrier from something on the other side of the wall.

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The use of the term “hermetic” requires clarification in all cases, and should be differentiated from the term “near hermetic.” The conditions of the application must be defined, e.g. temperature, pressure, identity of the penetrating species, barrier material, expected lifetime, etc. as well as the test method to verify performance. In the purest sense, hermetic means that absolutely nothing can penetrate a given barrier under specified conditions for the expected application duration.

Hermetic performance (hermeticity) is commonly observed for a barrier of fully dense metal, glass, or ceramic of adequate wall thickness. In general, even the most mobile species, such as lightweight gaseous atoms or molecules cannot penetrate these structures. For example, water, hydrogen, and helium can be contained indefinitely in steel vessels. Pressurized gas tanks can hold these gases indefinitely with no detectable leaks on the outside. However, if the temperature of the tanks is elevated for an extended period of time a substance can react with most materials over time, and decompose the barrier, ultimately destroying the sealing performance.

It is important to specify the temperature, pressure and time requirements of a hermetic sealing system and to identify the materials being applied.

In contrast to metals, metal-oxides and ceramics, organic polymers are penetrable by such species as water, hydrogen, and helium. Most everyone has seen a helium balloon deflate in a matter of a few days because the helium passes through the wall of a rubber balloon. In many cases, however, the penetration occurs at such low rates that their penetration is inconsequential to the contents of the vessel, and the seal is sometimes loosely referred to as hermetic. [4] This behavior is more correctly referred to as “near hermetic.”

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Sometimes, use of a near hermetic system in conjunction with an absorbent of the penetrating species can result in a truly hermetic performance for a short time. For example, if the penetrating species is water, and a water absorbent (or adsorbent) is integrated into the system, then, water will not begin penetrating the near hermetic material until the absorption capacity of the absorbent has been reached. This configuration allows the seal to appear to be hermetic for some time, before the absorbent is saturated and cannot absorb any more water.

In general, hermetic seals can be fabricated from metals,[5,6] semi-conductors,[7] metal-oxides, glasses[8] , and ceramics[9]. Near hermetic seals can be fabricated from a long list of polymers including epoxy, polyurethane, polyimide, polymethylmethacrylate, (PMMA) polytetrafluoroethylene, (PTFE) and its derivatives, e.g. Nafion .[10]

Hermetic seals may take many combinations including metal/metal, metal/glass glass/glass, glass/ceramic, ceramic/metal, ceramic/ceramic, metal/plastic, glass/plastic, ceramic/plastic.

Hermetic sealing is used to protect microelectromechanical (MEMS) devices,[11] especially for reliability.[12] Titanium-ceramic has been used as a hermetic seal for medical implantable devices, primarily for its biocompatibility, but also in part due to its radio frequency transparency and the ability to communicate with the embedded electronics of a device within a human patient.[13] Leadless chip carriers (LCC) have been sealed with high temperature cofired ceramics (HTCC) for a low cost approach to hermetic lid sealing.[14]

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In terms of housing material, several materials are widely used to create hermetic packages, including titanium and its alloys,[15] stainless steel, nickel, nickel-cobalt alloy, niobium, brass, copper, gold, aluminum, glass, ceramics, and many organic polymers. As described above, the performance of a given system may be hermetic or near hermetic, and each system requires careful characterization and testing to determine suitability in a given application. The materials and method of construction are the dominant aspect of hermetic performance.

A hermetic package can protect a device from corrosion by excluding water or oxygen from contacting the device. NdFeB magnets are highly susceptible to corrosion in moist environments. Clearly, the applications of NdFeB magnets can be expanded by use of hermetic protection.

In the case of titanium casings, the possible lifetime of a device can be many years because titanium has a high natural resistance to corrosion and oxidation, even when used for years in hostile biological or marine environments. Titanium is reliably laser welded, even at very thin wall dimension, e.g. less than 0.050" with weld penetration ranging from 0.005" to 0.250". Such titanium welds are typically rated to helium flow rates of less than 1 x 10-7 standard cubic centimeters/second.

Laser welding of titanium packages has the important advantage that the magnets inside the case are not heated, because the laser welding highly localizes the applied energy. This is important because heat demagnetizes, so the laser process preserves the permanent magnetization. Additionally, the highly localized energy minimizes stress on the joining materials and reduces overall welding cycle time as well.[16]

Additionally, titanium is not magnetic; it is paramagnetic, but, has a very low magnetic susceptibility, which is a measure of how a material responds to a magnetic field.

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When a magnet is passed near any metal, eddy currents form in the metal, and this is called the Lenz effect. Different metals show greater and lesser Lenz effect behavior. Of all metals, titanium shows the lowest Lenz effect, meaning it is affected less by magnetic fields than any other metal. The minimal Lenz effect for titanium allows patients with titanium implants, such as artificial joints, to be able to submit to a magnetic resonance imaging procedure without issue.

Other metals can be welded by a variety of techniques to achieve hermetic seal performance also. The choice of the metal for a hermetic package is application dependent. Some metals may also form hermetic seals by exploiting their eutectic properties.[17]

Glass and glass frit can be used to make a hermetic seal. Glasses can be applied by a variety of methods, including spraying, screen printing, extrusion, or sputtering. This variety of options makes glass a very versatile option for hermetic sealing. Glass seals generally are not mechanically very strong or resistant to shock and vibration loading, so, if an application requires high pressure, many cycles of pressure variation, or high vibration/shock loading, the mechanical properties of the glass should be well-understood before choosing it. In the case of a glass-to-metal seal, the coefficient of thermal expansion of the glass seals should be matched as closely as possible with the metal to which it is mating.

Hermetic Seals
Mechanism of Hermeticity

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Water is omnipresent, and threatens to damage virtually any material that can be hydrolyzed or oxidized, particularly if elevated temperatures and/or pressures are available.

To address the need to rigorously exclude water from a device surface, a suitable material must be chosen. For the most part, metals, metal-oxides (including glasses), and ceramics are intrinsically impermeable to small gas phase species, like water, hydrogen, and helium. Plastics and organic polymers are intrinsically permeable to water. It is common for plastics to absorb up to 2% of their weight in water. Therefore, in order to protect highly susceptible devices from small gaseous species like water vapor, metals, metal-oxides, and ceramics are preferred over organic polymers as protective materials of construction. The permeability/impermeability of any material is an intrinsic fundamental property of a given material.

As described above, however, the application conditions and test methods must be carefully described to choose the appropriate materials. In the case of a short term exposure, an organic polymer material may be preferable for reasons of cost, or ease of processing, relative to a metal, metal-oxide or ceramic. A low level of permeability may be acceptable, and choosing an organic polymer may provide other advantages, like cost, weight, or processing cycle time. Thorough knowledge of appropriate test methods should be available prior to package design.

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Common methods of fabricating hermetic seals include welding, thermocompression bonding, compression, and adhesion. A variety of welding methods are available including micro-plasma, electron beam, projection, friction, ultrasonic, resistance, brazing, and laser welding. The choice of welding method depends on the form factor requirements of the package, the metals being welded and the barrier performance required.

Laser welding has become very popular due to its speed and ability to make fine bonds. Additionally, laser welding can be done inside a glove box, giving the customer the option to choose a gas to trap inside the part, e.g. nitrogen or argon etc. to keep an inert atmosphere protecting the interior for the lifetime of the part. Laser welding can be applied to dissimilar metals and finds its value in part, due to the very fine, but deep, weld lines it can achieve. With a reasonable degree of automation applied to small parts, e.g. dimensions of a few inches, weld time can be less than 1 minute, with nominal welding speed of 5-10 inches per minute.

Titanium may be the most widely used metal for hermetic packaging, particularly for medical applications, and high performance seals have been widely achieved by use of laser welding it.[18] Titanium is an ideal material for hermetic sealing because of its relative inertness, especially to corrosion and oxidation. Additionally, thermoplastic welding has been used to create hermetic packages, with laser welding being the preferred method.[19] Plastics may offer better cost options in some cases, and lower weight, flexibility, and thermal insulation. The lower weight is especially important for aerospace applications where aircraft fuel economy is a major issue. Plastics are also transparent to wireless radio signals, enabling such communication from within the packages. However, polymers have the smallest operating temperature window relative to other types of hermetic seals. Laser welding can be applied to join dissimilar materials also.

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Thermocompression bonding is used widely in semiconductor packaging and is normally achieved by applying heat and pressure to join two metals together, commonly, gold, copper, tin, or aluminum.[20] In a thermocompressive bond, the metals diffuse into each other to create a monolithic polycrystalline structure. Thermocompression bonding requires extremely clean conditions, and the metal surfaces are normally etched to remove oxides prior to the bonding step. Thermocompression bonding is used to fabricate sensors and MEMS devices. [21]

Compression seals are, perhaps, the simplest and most well-known. A compression seal is formed when two parts are pressed tightly against each other resulting in an interface that does not allow gases to travel between the mating faces. Compression fittings are very common in residential applications for plumbing and gas connections. These seals are quick to form and inexpensive but require sustained mechanical force to function. They can hold the highest pressure of all the hermetic seal types and can survive temperature, mechanical and vibration loading better than glass or ceramic. Compression seals do not require matching of coefficient of thermal expansion.

Adhesion is a broad category of bonding that refers to a bond that occurs due to surface attractive forces between substrate and an adhesive. For example, application of a common adhesive like epoxy to a metal surface does not involve any phase change or diffusion processes. Instead, epoxy bonds with a surface as a result of the interaction between the chemical structure of the epoxy and the chemical structure of the substrate surface. Similarly, when glass-to-metal seals are formed, the glass is melted or softened, and it chemically bonds to metal oxides present on the surface of the metals, and may be considered an adhesive bond, much like epoxy. Chemical transformations at the interface may occur, but are not necessary. In some cases, the attractive forces of the chemical structures on the surface are enough to create a strong adhesive bond.

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Helium testing for hermetic behavior is a commonly used tool to identify the presence of leaks in a system intended to be hermetic. In one version, the device under test has a port with a shut-off valve built into it, to which a gas tight vacuum source can be connected. The valve is opened and the interior of the device is evacuated; the interior of the device is then subsequently backfilled with helium through the same port. After helium has filled the vessel, the valve is closed so no gas can escape through the port, and the device is disconnected from the vacuum source. Next, the entire device is placed in a helium-free vacuum chamber attached to a mass spectrometer. The pressure inside the vacuum chamber is reduced, and the effluent is directed through the mass spectrometer. If the mass spectrometer detects helium, this indicates that the device under test is the source of helium, and, that a pathway for helium to escape the intended seal exists. In this case, the intended hermetic seal would likely be deemed a failure. The rate of helium volume flow rate out of the device can be quantified by the mass spectrometer, and is normally expressed in units of standard cubic centimeters/second. [22] Generally a maximum volume flow rate is specified to define a FAIL criterion. If the volume flow rate does not exceed the specified threshold, then, the part is deemed to PASS.

For the case where the device under test does not have a vacuum port, and the interior volume is not easily accessible, an alternate helium leak test method may be used. For example, the volume inside a magnet encasement would not normally be accessible by a valved port. In this case, the part is placed in a vacuum chamber, and evacuated to an appropriate pressure, and then the entire vacuum chamber is backfilled with high pressure helium, in a so-called "helium bomb" configuration. In order to assure that helium is penetrating very small leak paths, the helium pressurization chamber step may be as long as 24 hours. Next, the helium outflow from the device is sensed with the mass spectrometer, just as before, and the rate of helium flow observed determines PASS/FAIL result. Commonly, flow rates as low as 1 x 10-9 standard cubic centimeters/second are measured.[23]

The use of helium in a chamber is often referred to as a "helium bomb test."

Hermetic Seals Testing

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Helium is the most advantageous gas to use for leak testing because the helium is composed of monatomic gas particles, which are very small, diffuse rapidly, and can penetrate extremely small openings quickly. Furthermore, helium is easily detected, and is inert. The inertness of helium may be the most important aspect of helium leak testing, because hermetic seals may be applied for sensitive electronic, magnetic, organic, mechanical, or medical assemblies which could suffer irreversible damage if a chemically reactive gas were used. Helium does not react chemically with any material, and cannot damage any surface it contacts in any way.

In still further variations, sensors may be integrated inside the target hermetically sealed volume to characterize humidity, temperature or corrosion, as a way to monitor the performance of the package. [24] These have been demonstrated for biomedical implantable devices where the integrity and durability of the seal is extremely crucial, because it may be operating in the application for decades. Any contamination, leak, or exposure can cause detrimental results.

Additionally, since water is often the material of interest in a hermetic package, thermogravimetric analysis (TGA) is also used to evaluate the integrity of a seal.[25] TGA is an analytical technique where a sample is placed on a balance pan inside a heating chamber, and its weight is monitored as a function of the chamber temperature. In the case of water, it is easy to observe a water weight loss when the sample reaches 100oC and any absorbed/adsorbed water will boil away.

TGA is a very widely used technique for quantifying moisture content in applications ranging from foods to electronic components. This is a very convenient method for hermetic characterization because TGA is a relatively inexpensive tool, and it gives a direct measurement of the water content of the vessel under test. Generally TGA testing would be applied to polymers since solid, polycrystalline metals have no moisture absorption behavior. TGA can characterize hermetic or near hermetic material systems. In a typical procedure, the vessel under test is exposed to some standard known moisture condition, e.g. 85oC/85% relative humidity, for some specified time, e.g. 24 hours etc.

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Next, the vessel is placed in the TGA instrument, and the amount of moisture in the samples is quantified. By knowing the amount of moisture tolerable in the application of interest, it can be determined if the near hermetic behavior is adequate.

In some cases, including testing of integrated circuit packages, rubber tires, and aerospace composites, an optical technique that detects gas leaks called shearography can be used. [26] Shearography is also called speckle shearing interferometry because it depends on the laser speckle effect, the scattering of laser light by an optically rough surface. In shearography, two speckle patterns are added to create an interferometric speckle pattern that is imaged by a camera. One speckle pattern is created by the laser directly, and the second speckle pattern is created by laser light that has passed through a shearing device, like a prism, and as a result has a different phase, and experiences a different overall distance traveled between source and detector, relative to that from the light directly from the laser.

By correlating speckle patterns, a fringe pattern can be generated. This is a laser-based, non-destructive, interferometric test, where the interference of laser speckle patterns can identify strain in the surface of the device under test. In short, shearography measures the spatial derivative of the displacement of the walls of a vessel under test, not just the position "before and after" and can measure the strain directly. [27]

In a typical test, a test specimen is placed in a chamber whose pressure is varied. During the test, the walls of the test specimen are illuminated with a laser whose scattered light is collected and processed in accordance with the principles of shearography described above. If the vessel does not leak, the walls of the vessel will deform with the pressure variation and maintain the deformed mechanical state while the pressure is held constant. If the vessel leaks under constant pressure, however, the inside and outside pressures will quickly equilibrate and the vessel will return to its original shape, resulting in a time-dependent deformation. Minute changes in vessel shape are detected with shearography, and typical test time is less than a few minutes per sample.

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In general, a hermetic sealing vessel should not only prevent gases, liquids, or particulate from penetrating, but, it should have carefully designed mechanical features too, to survive its application environment. One of the most important mechanical aspects of a hermetic seal is the matching of coefficient of thermal expansion of interfacing materials. Common light bulbs are glass-to-metal hermetic seals. Glass-to-metal hermetic seals can be formed by pressing metal into molten or softened glass.[28] The highest temperature performing hermetic seals, in terms of temperature and pressure fluctuations are ceramic-to-metal, but these are the most complex and expensive to make.

In addition to the thermal expansion considerations, it is also important to understand the pressure and temperature conditions that the vessel will experience in application, particularly if there is gas trapped inside the vessel, as well as the mechanical form factor of the protective vessel.

In the case of sealed permanent magnets, it is normally desirable to make the protective vessel walls as thin as possible because magnetic field strength decreases with the inverse square of the distance. This means that if the distance from the magnet is doubled from "d" to "2d", the magnetic field strength at "2d" will be 1/(22) = 1/4 of the value at "d." Similarly, if you move "3d" away, the magnetic field strength will drop to 1/(32)=1/9th of the value at "d". The magnetic field strength falls off with distance rapidly, so, thicker walls diminish the performance of the magnet.

Given that thinner walls are better for delivering magnetic field strength, special engineering approaches may be required to maximize the vessel integrity. For example, the pressure and temperature likely will fluctuate during application, and this can cause the protective housing on the permanent magnet to distort. Many cycles of distortion can weaken a metal housing, and jeopardize the hermetic seal. The amount of distortion allowed must be carefully managed by the assembly designer to minimize the risk of mechanical failure of the hermetic seal.

Hermetic Seals Footnotes

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