Magnetic Properties of Materials Used in Electron Gun Systems

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Introduction

Electron beams are used in a variety of applications, such as in particle accelerators, electron microscopes, and electron beam lithography. In these applications, precise control over the path and spatial distribution of the electron beam is essential for accurate and reliable performance.

Various materials are in proximity to the electron beam in vacuum systems. These materials can influence the electron beam in both intended and unintended ways.

In this document, we will briefly review 1) simplified electron beam control with electron optics, 2) materials used in vacuum systems and their magnetic properties, and 3) various unintended magnetic effects and how they can be mitigated.

Later in the document we will be discussing the material and magnetic properties of titanium and will also briefly discuss the properties of hydrogen diffusion with these materials in ultra-high (UHV) and extremely high vacuum (XHV) systems. At the end of the document, we also provide some comments to frequently asked questions.

Please note that the content in this document is only intended to provide a starting point for the reader to further research this topic.

Electron Optics

The electron optics used in an electron gun system utilize both electric fields (deflection plates) and magnetic fields (coils). The optical elements are typically carefully designed to precisely alter the trajectory of the beam as well as its cross-sectional form and focus.

Electric Field Optics

Electric fields generated across the opposing deflection plates of the electron gun system optics exert a force on the negative charges in the electron beam, causing an acceleration perpendicular to their original path, with the electron deflecting away from the negatively charged plate. The magnitude of this acceleration depends on 1) the strength of the electric field (the voltage across the plates, separation distance of the plates), 2) the mass and velocity of the particle, 3) plate geometry, and 4) the dielectric of the material present between the plates (in this case, vacuum).

By manipulating the electric field across the deflection plates, the trajectory of the electron beam can be altered to direct it at specific targets or to raster it in various pre-determined patterns.

Magnetic Field Optics

The magnetic fields generated by the coils in electron optics have a significant impact on both the trajectory and form of the electron beam.

Beam Focus. One key function of these magnetic fields is to *focus* the electron beam. Magnetic lenses, formed by cylindrical coils, are used to achieve this. The current passing through these coils generates a magnetic field that exerts a force on the electrons, known as the Lorentz force. The direction of this force is perpendicular to both the velocity of the electrons and the magnetic field direction. The orientation of the magnetic field and the resulting Lorentz force forces electrons in the beam to converge to a small focal spot. Careful design of magnetic fields inside the lens provides precise control of beam convergence and focused spot size.

Beam Deflection. Magnetic fields can also be used to *deflect* the path of the electron beam. Deflection coils generate magnetic fields that are perpendicular to the direction of electron motion. The fields are linear, and not cylindrically symmetric. As the electrons move through these magnetic fields, the Lorentz force causes them to experience a perpendicular acceleration, resulting in a change in their trajectory. By varying the strength and direction of the magnetic field, the electron beam can be precisely steered and scanned to specific positions.

Electron Spin. Additionally, magnetic fields find applications in manipulating the spin of electrons, as seen in electron spin resonance spectroscopy. By applying a magnetic field along a specific axis, the alignment of electron spins can be controlled, influencing their behavior and interactions with other particles or materials.

In summary, the magnetic fields generated by the coils in electron gun system optics serve to focus, deflect, and control the path and spin of electrons in the electron beam. This control is essential for various scientific and technological applications where precise manipulation of the beam is required.

Magnetic Permeability. Magnetic permeability is a physical property of materials that describes their ability to respond to a magnetic field. It is a measure of how much a material can be magnetized in the presence of an external magnetic field. Specifically, magnetic permeability is defined as the ratio of magnetic flux density to the magnetic field strength in a material. In electromagnetism, permeability is the measure of magnetization produced in a material in response to an applied magnetic field. Permeability is typically represented by the Greek letter μ. It is ratio of the magnetic induction B to the magnetizing field H in the material.

In SI units, permeability is measured in henries per meter (H/m), or equivalently in newtons per ampere squared (N/A^2). The permeability constant μ_0, also known as the magnetic constant or the permeability of free space, is the proportionality between magnetic induction and magnetizing force when forming a magnetic field in a classical vacuum.

Materials with high magnetic permeability are easily magnetized by an external magnetic field, while materials with low magnetic permeability are more difficult to magnetize. The magnetic permeability of a material also affects its ability to conduct magnetic flux, which is the flow of magnetic field lines through a material.

Relative Magnetic Permeability Units

Relative Permeability is a dimensionless quantity that compares the permeability of a material (μ) to the permeability of free space (μ_0). It is calculated by dividing the permeability of the material by the permeability of free space:

Relative Permeability = μ / μ_o

Since it is a ratio of two permeability values, relative permeability has no units. It is a convenient measure to compare magnetic permeability of materials without the units.
If we know the permeability of a material in H/m, we can calculate its relative permeability by dividing it by the permeability of free space ($4\pi \times 10^{-7}$ H/m). If we know the relative permeability of a material, we can calculate its permeability in H/m by multiplying it by the permeability of free space ($4\pi \times 10^{-7}$ H/m).

The unit of magnetic permeability is henries per meter (H/m) in International System of Units (SI), which is equivalent to 1 kg*m/sec^{2}A^2.

Changes in Magnetic Permeability

As we will discuss in more detail below, machining and manufacturing operations can sometimes alter the original magnetic permeability properties of a material.

Categories of Magnetic Permeability

In physics, several different types of material magnetism have been described. Ferromagnetism (along with the similar effect ferrimagnetism) is the strongest form of magnetism and is responsible for the common phenomenon of magnetism diversly seen in everyday life- from refrigerator magnets to the electromagnetic effects seen in electric motors and transformers.

Other substances can respond weakly to magnetic fields with three other basic forms of magnetism- paramagnetism, diamagnetism, and antiferromagnetism These forces are typically very weak and can only be detected by sensitive instruments in a laboratory. However, these effects can be a factor in sensitive electron beam systems.

Ferromagnetic Materials. These materials have a very high magnetic susceptibility and are strongly attracted to a magnetic field (e.g., magnet- permanent or electro). They can also retain their magnetization even after the external magnetic field is removed, a phenomenon referred to as remanence. They typically have a relative magnetic permeability value very much greater than 1.0 with values often of several thousand (see table below).

All common carbon steels (including mild steel), low alloy steels and tool steels are ferromagnetic. Some other metals such as nickel and cobalt are also ferromagnetic.
All stainless steels with the exception of the austenitic grades (such as 316L SS) are also magnetic – this includes: 1) all ferritic grades (e.g. 430, AtlasCR12, 444, F20S), 2) all duplex grades (e.g. 2205, 2304, 2101, 2507), 3) all martensitic grades (e.g. 431, 416, 420, 440C) and 4) all precipitation hardening grades (e.g. 630/17-4PH). Even though the duplex grades are mixtures of austenite and ferrite they are still strongly attracted to a magnet. (*Ref: Atlas Steels- Tech Note No. 11*).

In summary, carbon steels, low alloy steels, and tool steel, including Stainless Steel with ferritic and martensitic grades are ferromagnetic and are considered "*magnetic*" materials. Stainless Steel 316L, an alloy that contains iron but with an austenitic crystal structure (grade) is not magnetic, unless there have been changes to its crystal structure during a manufacturing operation (see below).

Paramagnetic Materials. These materials have a minimally positive magnetic susceptibility, which means that they are weakly attracted to a magnetic field. Examples of paramagnetic materials include aluminum, magnesium, platinum, 316L stainless steel (austenitic grade) and titanium. They typically have very low relative magnetic permeability values, usually just a fraction above 1.0 (see table below)

In summary, most non-ferrous metals such as aluminum, titanium, and their alloys are non-magnetic. Austenitic stainless steels, both the common 300-series (Cr-Ni) and the lower nickel 200-series (Cr-Mn-Ni) are non-magnetic. It is common for wrought austenitic stainless steels to contain a very small amount of ferrite, but this is not sufficient to significantly affect magnetic performance except in very critical applications (*Ref Atlas Steels- Tech Note No. 11*). Inconel is also paramagnetic, even though it has a large proportion of nickel (which is magnetic) as part of its alloy.

Diamagnetic Materials. These materials have a negative magnetic susceptibility (permeability less than 1.0), which means that they are weakly repelled by a magnetic field. Examples of diamagnetic materials include water, most organic compounds, copper, silver, gold, carbon, mercury, and lead.

Other Factors. The magnetic permeability of a material also depends on factors such as temperature and the strength of the external magnetic field. In addition, some materials can exhibit different magnetic properties depending on their microstructure, such as the presence of impurities or defects. In some metals, at elevated temperature (their Curie Temperature) they can change from ferromagnetic to non-magnetic. For common carbon steels this happens at about 768°C.

Overall, the magnetic permeability of a material is an important factor in determining its behavior in the presence of a magnetic field and is a key consideration in many technological applications.

Extraneous Magnetic Fields

If there are extraneous unintended magnetic fields along the path of the electron beam, they can deflect or distort the beam from its intended path and form or profile, which can result in inaccurate or unreliable results.

Sources of Unintended Magnetic Fields

Magnetic fields can unintentionally be introduced from structures used to create the vacuum environment for the electron beam, such as the metal vacuum chamber structures, flanges, and support materials and fittings within the vacuum space. As previously noted, these poorly defined and uncharacterized fields can deflect the path or distort the form of the electron beam. This is especially a concern when the electron beam application requires precision and accuracy such as in particle accelerators, electron microscopes, and electron beam lithography. In these applications, precise control over the path and form of the electron beam is essential for accurate and reliable performance.

Unintended sources of magnetic field in the electron beam environment include 1) eddy currents, 2) materials with high magnetic permeabilities such as ferromagnetic materials, and 3) unintended changes to magnetic properties caused by machining and manufacturing operations.

Eddy Currents. Metal vacuum chamber structures can create magnetic fields due to a phenomenon known as eddy currents. When a changing magnetic field passes through a conductive material, such as metal, it can induce electric currents to flow in the material. These currents, in turn, create their own magnetic fields, which can interact with the electron beam. To avoid these problems, it is important to design vacuum chambers and other equipment used in electron beam applications with magnetic shielding and other measures to minimize the impact of eddy currents and other sources of magnetic fields. By minimizing magnetic field interference, researchers and engineers can ensure that their electron beam applications are accurate, reliable, and effective.

Materials Used in Vacuum Systems

Typically, Stainless Steel 316L and Titanium (and it alloys), materials commonly used in vacuum hardware, have relative magnetic permeability values of only a fraction above 1.0. In certain instances, however, parts of a Stainless Steel structure can have values much greater than 1.0. This is often related to various manufacturing operations such as bending and welding that can alter its normal crystal structure.

As noted in the table below, 316L Stainless Steel, titanium and its alloy, and aluminum all have relatively very low permeability values, which makes them good choices for vacuum chambers used in electron beam systems.

In contrast, high permeability materials such as iron and carbon steel should be avoided in these applications to minimize interference with the electron beam trajectory, profile, and focus.

Ceramic and glass materials have a permeability value of 1.0, which means they are non-magnetic and suitable for use in vacuum chamber hardware where magnetic interference must be minimized.

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Machining / Manufacturing Operations Overview

CNC (computer numerical control) operations controlling milling machines and lathes using optimized cutting tool pressures with lubrication are typically used at Kimball Physics with no measurable effects on 316L Stainless Steel and Titanium magnetic permeability properties.

Several other methods are available to create the final form of a metallic structure. The terms used to describe these various processes can be confusing. The magnetic permeability in some materials can be influenced by how the material is manufactured- cold working, work hardening, tempering, bending, casting, and welding to name a few. We will briefly cover the more common processes below.

"Wrought" is a term that simply means "worked". In ancient times, wrought iron was produced by hammering a heated metal repeatedly.

Metalworking is the process of shaping and forming metals to create various metal components.

Recrystallization is a process in metals by which deformed grains are replaced by a new set of non-deformed grains that nucleate until the original deformed grains have been entirely consumed. This is important concept when taking about cold and hot work shaping processes.

Cold working involves various forming and shaping processes that are applied below the metal's recrystallization temperature, usually at the ambient temperature. This process increases ultimate tensile strength, yield point, and fatigue strength, but decreases resistance to corrosion.

In the precision machining industry, cold working processes can include thread rolling, thread forming, swaging, crimping, staking, planishing and metal spinning. Steel bars, commonly used as a starting material, are typically machined by cold drawn (cold worked). Unlike hot working, cold working causes the crystal grains and inclusions to distort following the flow of the metal, which may cause work hardening and anisotropic material properties. Work hardening makes the metal harder, stiffer, and stronger, but less plastic, and may cause microscopic cracks in the piece.

Hot working or forming involves various forming and shaping processes that are applied above the metal's recrystallization temperature. Examples of these forming techniques include hot rolling, forging, welding, etc. These processes can alter the grains to a different crystal structure- and in some cases also change the magnetic permeability .

Welds and Castings. Castings in austenitic stainless steels have slightly different compositions compared to their wrought counterparts. The cast version of 316L for instance is grade CF-3M. Most "austenitic" cast alloys are very deliberately made so that they have a few percent of ferrite – this helps prevent hot cracking during casting.

A weld can be viewed as a small, long casting, and for the same reason as detailed above, austenitic welds have about 4 – 8% ferrite. In the case of both welds and castings, the small amount of ferrite results in a small amount of magnetic response, but it can be readily detected with a good hand-held magnet. With a suitable "ferrite meter" this magnetic response can in fact be used to measure the amount of ferrite in a weld.

Materials Used in Kimball Physics Vacuum Systems

Stainless Steel.

316L Stainless Steel is predominately composed of iron, with 16-18% chromium, 10-14% nickel, 2-3% molybdenum, and small percentages of carbon, manganese, and silicon. The magnetic permeability of stainless steels can vary, depending on its composition and microstructure. Austenitic stainless steels (316L SS), generally have a low magnetic permeability, typically around 1.0 (to learn more about the units to measure magnetic permeability, and the values of various materials, please see the content above). However, the magnetic permeability of stainless steel can increase if it undergoes certain types

of mechanical and heat processing as noted above.
Welding and casting can cause regions of ferrite formation within the austenitic material, which can result in a small magnetic response which is measurable and can have an impact on certain applications, such as in magnetic sensors or electromagnetic shielding.

Only a limited number of Kimball Physics Multi-CF hardware parts require welding. The method of welding we use limits the introduction unintended magnetic effects.

Titanium. Titanium and its alloys are known for their high strength-to-weight ratio, with high strength and low density, low thermal expansion,

Table of Relative and Magnetic Permeability of Selected Materials

Material	Relative Magnetic Permeability μ/μ_0	Magnetic Permeability μ (H/m)	Comments
316L Stainless Steel (Austenitic)	1.003 – 1.05	1.260×10^{-6} – 8.8×10^{-6}	Paramagnetic
Titanium (Pure)	1.00001		Paramagnetic
Titanium Alloy (Ti-6Al-4V)	1.00001		Paramagnetic
Aluminum (Pure)	1.000022	1.256665×10^{-6}	Paramagnetic
Inconel 600 (6-10Fe, 14.7-17Cr, 0.15C, rem Ni)	1.01		Paramagnetic even with high nickel content of 50-55%
Iron (Pure)	200000	2.5×10^{-1}	Ferromagnetic
Carbon Steel	100	1.26×10^{-4}	Ferromagnetic
Stainless Steel Ferritic (annealed)	1000 – 1800	1.26×10^{-3} – 2.26×10^{-3}	Ferromagnetic
Stainless Steel Martensitic (annealed)	750-950	9.42×10^{-4} – 1.19×10^{-3}	Ferromagnetic
Stainless Steel Martensitic (hardened)	40 – 95	5.0×10^{-5} – 1.2×10^{-4}	Ferromagnetic
Nickel	100-600	1.26×10^{-4} – 7.54×10^{-4}	Ferromagnetic
Alumina (Ceramic)	1.00001		Paramagnetic
Glass	1.0		Paramagnetic
Air	1.00000037	$1.25663753 \times 10^{-6}$	
Vacuum	1.0	$1.25663706212 \times 10^{-6} = \mu_0$	
Copper	0.999994	1.256629×10^{-6}	Diamagnetic
Water	0.999992	1.256627×10^{-6}	Diamagnetic
Notes:	https://en.wikipedia.org/wiki/Permeability_(electromagnetism)		

and relatively high melting point. It is a non-magnetic (paramagnetic) metal and has a magnetic permeability of approximately 1.0. This means that they are not affected by magnetic fields and does not exhibit any magnetic properties. It readily forms a tenacious oxide surface on the bulk metal, providing excellent resistance to corrosion and significantly reduces diffusion of hydrogen from the bulk metal.

In summary, materials and processes used by Kimball Physics for vacuum hardware, including austenitic stainless steels (316L SS) and titanium and its alloys, have very low magnetic permeability with either minimal or no magnetic field artifacts introduced into our electron beam systems. Please see the FAQ section below for more information about Titanium and hydrogen diffusion in ultra-high (UHV) and extreme-high vacuum applications.

FAQ

1) Does titanium have any changes with its magnetic permeability if it is processed mechanically, such as by cold working or bending?

No, titanium is a non-magnetic metal and is not affected by magnetic fields, regardless of its mechanical processing. The magnetic permeability of titanium is very close to that of a vacuum, which is approximately 1.0, meaning that it is not magnetic and does not exhibit any magnetic properties.
Titanium's non-magnetic properties make it a useful material in applications where magnetic interference is a concern, such as in electronic devices or medical implants that require magnetic resonance imaging (MRI) scans. In fact, titanium is one of the preferred materials for implants in MRI-compatible medical devices because it does not produce any artifacts or distortions in the images.
In summary, titanium is a non-magnetic metal and does not experience any changes to its magnetic permeability, even when it is processed mechanically.

2) Does welding of stainless steel affect its magnetic permeability ?

Yes, welding of stainless steel can affect its magnetic permeability, depending on the welding process and the specific composition of the stainless steel being used.
Welding involves heating the material to a high temperature, which can cause changes in the microstructure of the metal, including changes in its magnetic properties. In particular, the heat from welding can cause the formation of ferrite, which is a magnetic phase of iron that can be present in some types of stainless steel.
Stainless steels are typically classified into different grades based on their microstructure and chemical composition. The two most common types of stainless steel are austenitic and ferritic. Austenitic stainless steels are generally non-magnetic, while ferritic stainless steels can be magnetic.
If an austenitic stainless steel is welded, it can become more magnetic if the welding process causes the formation of ferrite in the weld zone. This is known as weld decay, and it can result in a material that is more susceptible to corrosion and other types of degradation.
However, it is possible to minimize the magnetic effects of welding on stainless steel by using the appropriate welding technique and selecting a grade of stainless steel that is less susceptible to weld decay. For example, some grades of stainless steel are designed to be more resistant to the formation of ferrite during welding, which can help to minimize any changes in magnetic permeability.
In summary, welding can affect the magnetic permeability of stainless steel, particularly if the welding process causes the formation of ferrite in the weld zone. However, the degree of change in magnetic properties will depend on the specific type of stainless steel being used and the welding process employed.

3) Are there effects on material properties of 316L SS (specifically magnetic permeability) with CNC Machining vs. Welding?

When manufacturing vacuum chambers, there are two common methods: 1) welded components, joining together multiple individual components to create the vacuum chamber, and 2) CNC machining which involves manufacturing the vacuum chamber from a single block or monolith of material with no welding operations.

From a magnetic permeability and structural precision standpoint, CNC machining is superior to welding. Welding and cold working can change the crystal structure of the metal, which can result in increased magnetic permeability. This increase in magnetic permeability can introduce artifacts into the beam trajectory, profile, and focus.

CNC machining, on the other hand, ensures that the vacuum chamber has a uniform crystal structure, resulting in minimal magnetic permeability. CNC machining also ensures that the vacuum chamber has precise structural dimensions, orientations, and tolerances, resulting in a vacuum chamber that is structurally sound and meets the required specifications.

Conclusion:

In conclusion, 316L stainless steel is an excellent choice of material for vacuum chambers used in electron beam systems due to its high corrosion resistance, high-temperature resistance, and low magnetic permeability. When manufacturing vacuum chambers, CNC machining is a superior method compared to welding, as it ensures that the vacuum chamber has a uniform crystal structure, resulting in minimal magnetic permeability and precise structural dimensions and tolerances. By using 316L stainless steel and CNC machining, we can manufacture vacuum chambers that meet the required specifications and ensure that electron beam systems operate with maximum efficiency.

4) What are advantages of Titanium for ultra (UHV) and extreme (XHV) high vacuum chambers?

Titanium is a material that is often used for ultra-high (UHV) and extreme-high (XHV) vacuum chambers. It is a popular choice because of its low outgassing rate, low magnetic permeability, excellent corrosion resistance, and high strength-to-weight ratio. Titanium also has a low thermal expansion coefficient, making it a good choice for applications that require stability over a wide temperature range. In addition, titanium has a lower magnetic permeability than stainless steel, which makes it ideal for electron beam systems that may be sensitive to extraneous magnetic fields.

While we are discussing titanium and XHV systems, one issue that can arise with vacuum chambers at extreme vacuum is the diffusion of hydrogen into the vacuum space from out of the bulk metal. Hydrogen can diffuse through the metal of the chamber and contaminate the vacuum space. This can be particularly problematic in ultra and extreme high vacuum systems, where even small amounts of contamination can cause issues.

Titanium has better hydrogen diffusion properties than 316L stainless steel. This is because titanium forms a protective oxide layer on its surface that prevents hydrogen from diffusing through the metal surface. In contrast, stainless steel is more prone to hydrogen diffusion, particularly if it has been cold worked or welded.

The advantages of titanium and TiN coatings are nicely described in the following experiment (see reference: Vacuum characteristics of Titanium)

In the measurement of the outgassing rate of small samples, it was found that the outgassing rate of titanium decreased 1.5 times faster than that of stainless steel. Furthermore, a TiN coating was found to reduce the total amount outgassed from 1.78×10^{-2} to 1.17×10^{-2} Pa m3 in the measurement of titanium and from 1.02×10^{-1} to 9.22×10^{-3} Pa m^3 in the measurement of stainless steel. In a mass analysis of the gases from the samples, the ion current of hydrogen from chemically polished titanium, chemically polished and TiN-coated titanium, and TiN-coated stainless steel decreased after attaining a maximum, while that from buffed and electropolished stainless steel increased continuously during the baking at 200 °C.

Considering these results, a vacuum chamber made of titanium coated with TiN and a vacuum chamber made of electropolished stainless steel were prepared and pumped down into XHV region. The pressure of the titanium chamber reached 6×10^{-11} Pa after a 312 h baking at 250 °C, while the stainless steel chamber required a 434 h baking at 250 °C to attain the ultimate pressure of 7×10^{-11} Pa. The pressure of the titanium chamber decreased more rapidly than that of the stainless steel chamber during the baking at 250 °C.

In conclusion, titanium is an excellent choice for ultra and extreme high vacuum chambers due to its low outgassing rate, low magnetic permeability, excellent corrosion resistance, and high strength-to-weight ratio. It also has better hydrogen diffusion properties than 316L stainless steel. When designing vacuum chambers, it is important to consider the properties of the materials used and how they will impact the performance of the electron beam system. By selecting the appropriate material and manufacturing method, we can ensure that vacuum chambers perform optimally and maintain the required vacuum levels.

5) Do thread forming fabrication techniques in 316L SS cause working hardening of the metal and possible changes in its crystal structure from austenitic to a crystal structure that is ferromagnetic?

Thread forming fabrication techniques can cause working hardening of 316L stainless steel, but it is *unlikely* to change its crystal structure from austenitic to a crystal structure that is ferromagnetic.
316L stainless steel is an austenitic stainless steel, which means it has a face-centered cubic (FCC) crystal structure at room temperature. This crystal structure is non-magnetic, and the material is generally considered to be non-magnetic in its annealed condition.
However, when stainless steel is subjected to mechanical deformation, such as during thread forming, the metal can become work hardened. Work hardening occurs when the metal is deformed by cold working, which causes the dislocation density to increase and the material to become harder and stronger. This work hardening effect can increase the tensile strength of the material, but it can also reduce the ductility and toughness of the metal.

While it is possible for working hardening to cause a minimal increase in magnetic permeability, it is unlikely to change the crystal structure of the 316L stainless steel from austenitic to ferromagnetic. For this to occur, the metal would need to be heated above its critical temperature (around 1450°F) and then rapidly cooled, which is known as quenching. This process would cause the crystal structure to transform from austenitic to ferritic, which is ferromagnetic. However, thread forming processes typically do not involve heating the metal to such high temperatures, and so the crystal structure of the 316L stainless steel is unlikely to change from austenitic to ferromagnetic.

6) What effects on permeability would welding two pieces of 316L SS cause. Is its effect significantly larger the effects of work hardening?

Welding two pieces of 316L SS can cause an increase in magnetic permeability compared to the base metal due to the formation of ferrite in the weld zone. This effect can be significant and is generally larger than the effects of work hardening.
316L SS is an austenitic stainless steel, which has a low magnetic permeability in its annealed condition. However, during welding, the material undergoes thermal cycling, which can cause the formation of ferrite in the weld zone. Ferrite is a different crystal structure than the austenitic structure of the base metal, and it has a higher magnetic permeability than austenitic stainless steel. Therefore, the presence of ferrite in the weld zone can cause an increase in magnetic permeability.
The amount of ferrite in the weld zone depends on several factors, such as the composition of the base metal and the welding process parameters, including welding temperature and cooling rate. The ferrite content can be controlled by adjusting the welding parameters and by using filler metals with a specific ferrite content.
The increase in magnetic permeability due to welding can be significantly larger than the effects of work hardening, especially in the weld zone. Work hardening can cause a small increase in magnetic permeability, but it is generally much smaller than the increase due to the presence of ferrite. However, the effects of work hardening can be significant in areas adjacent to the weld zone where the material has been deformed during welding.
In summary, welding two pieces of 316L SS can cause an increase in magnetic permeability due to the formation of ferrite in the weld zone. This effect can be significant and is generally larger than the effects of work hardening. The amount of ferrite in the weld zone depends on several factors, and it can be controlled by adjusting the welding parameters and by using filler metals with a specific ferrite content.

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