

Guide for the Fusion Welding of Titanium and Titanium Alloys



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An American National Standard

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American National Standards Institute
May 20, 2021

Guide for the Fusion Welding of Titanium and Titanium Alloys

3rd Edition

Revises AWS G2.4/G2.4M:2014

Prepared by the
American Welding Society (AWS) G2 Committee on Joining Metals and Alloys

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

The standard *Guide for the Fusion Welding of Titanium and Titanium Alloys* provides instructional guidance for the welding of titanium and titanium alloys. This guide explains processes, equipment, materials, workshop practices, joint preparation, welding technique, tests, and the repair of discontinuities.



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Foreword

This foreword is not part of this standard but is included for informational purposes only.

The American Welding Society formed the G2 Committee on the Joining of Metals and Alloys in 1992 in response to an industry demand for information on welding the metals and alloys that have not been covered by other documents and committees. This document is written by the G2 Committee on the Joining of Metals and Alloys.

This guide makes use of both U.S. Customary Units and the International System of Units (SI). The measurements are not exact equivalents; therefore, each system must be used independently of the other, without combining values in any way. In selecting rational metric units, the AWS A1.1, *Metric Practice Guide for the Welding Industry*, and the International Standard ISO 544, *Welding consumables — Technical delivery conditions for welding filler metals — Type of product, dimensions, tolerances and markings*, are used where suitable. Tables and figures make use of both U.S. Customary and SI Units, which, with the application of the specified tolerances, provide for interchangeability of products in both the U.S. Customary and SI Units.

The evolution of AWS G2.4/G2.4M, *Guide for the Fusion Welding of Titanium and Titanium Alloys*, is shown below:

AWS G2.4/G2.4M:2007	<i>Guide for the Fusion Welding of Titanium and Titanium Alloys;</i>
AWS G2.4/G2.4M:2014	<i>Guide for the Fusion Welding of Titanium and Titanium Alloys;</i>
AWS G2.4/G2.4M:2021	<i>Guide for the Fusion Welding of Titanium and Titanium Alloys</i>

A vertical line in the margin or underlined text in clauses, tables, or figures indicates an editorial or technical change from the 2014 edition.

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS G2 Committee on Joining Metals and Alloys, American Welding Society, 8669 NW 36 St, # 130, Miami, FL 33166.

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Guide for the Fusion Welding of Titanium and Titanium Alloys

1. General Requirements

1.1 Scope. This guide provides information on welding processes and procedures that are recommended for use in titanium fabrication. The document presents detailed and up-to-date technical information on the best practices to allow first time fabricators of titanium as well as established fabricators to join titanium parts into high quality components.

Although this guide is not written with mandatory requirements, mandatory language, such as the use of “shall,” will be found in those portions of the document where failure to follow the instructions or procedures could produce inferior, misleading, or unsafe results.

1.2 Units of Measure. This standard makes use of both the U.S. Customary Units and the International System of Units (SI). The latter are shown within brackets ([]) or in appropriate columns in tables and figures. The measurements may not be exact equivalents; therefore, each system must be used independently.

1.3 Safety. Safety and health issues and concerns are beyond the scope of this standard and therefore are not fully addressed herein. Safety and health information is available from the following sources:

American Welding Society:

- (1) ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*
- (2) AWS Safety and Health Fact Sheets
- (3) Other safety and health information on the AWS website

Material or Equipment Manufacturers:

- (1) Safety Data Sheets supplied by materials manufacturers
- (2) Operating Manuals supplied by equipment manufacturers

Applicable Regulatory Agencies

Work performed in accordance with this standard may involve the use of materials that have been deemed hazardous and may involve operations or equipment that may cause injury or death. This standard does not purport to address all safety and health risks that may be encountered. The user of this standard should establish an appropriate safety program to address such risks as well as to meet applicable regulatory requirements. ANSI Z49.1 should be considered when developing the safety program.

2. Normative References

The documents listed below are referenced within this publication and are mandatory to the extent specified herein. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. (Informative standards and specifications for titanium fabrication are available in Annexes C and D.)

American Welding Society (AWS) documents:

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*;

AWS A5.12M/A5.12 (ISO 6848:2004 MOD), *Specification for Tungsten and Oxide Dispersed Tungsten Electrodes for Arc Welding and Cutting*;

AWS A5.16/A5.16M (ISO 24034:2010 MOD), *Specification for Titanium and Titanium Alloy Welding Electrodes and Rods*;

AWS A5.32M/A5.32 (ISO 14175:2008 MOD), *Welding Consumables—Gases and Gas Mixtures for Fusion Welding and Allied Processes*; and

AWS B2.1/B2.1M, *Specification for Welding Procedure and Performance Qualification*.

American National Standards Institute (ANSI) document:

ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*

ASME International document:

ASME BPVC-IX, ASME Boiler and Pressure Vessel Code (BPVC), Section IX, *Welding, Brazing, and Fusing Qualifications*

3. Terms and Definitions

AWS A3.0M/A3.0, *Standard Welding Terms and Definitions*, provides the basis for terms and definitions used herein. However, the following terms and definitions are included below to accommodate usage specific to this document.

alpha case. Alpha case is an oxygen-rich phase that forms beneath the normal titanium surface oxide when the surface of titanium is exposed to elevated temperatures in air or other oxidizing media. On extended exposure to higher temperatures the normal surface oxide is thickened, then is essentially dissolved into the metal, leading to the oxygen rich zone near the surface.

Alpha case may occur during hot working, heat treatment, and casting processes. Alpha case is hard and brittle and thus subject to crack initiation under conditions of fatigue or impact. Alpha case may contain a series of microcracks that are potential points of fatigue crack initiation and may be notch sensitive leading to cracking in fabrication or in service. Surface alpha case can be removed using grinding or machining processes or by the use of chemical milling (i.e., acid pickling).

For all-alpha grades the term alpha case is somewhat confusing so the term “oxygen enriched surface” is commonly used instead. Alpha case or oxygen enriched surface should be distinguished from surface oxidation, which is sometimes deliberately enhanced (thickened) either electrolytically or thermally to enhance corrosion resistance or other properties.

alpha grades or alloys. The alpha (α) grades or alloys are generally weldable and nonheat treatable. They are materials with relatively large amounts of alpha stabilizers and low concentrations of beta (β) stabilizers. They are sometimes referred to as having predominately an alpha phase. They have low to medium strength, good notch toughness, and good resistance to creep at elevated temperatures. A common alpha alloy is commercially pure (CP) titanium.

allotrope. An allotrope is one of two or more crystallographic structures that can exist in an element or alloy such as those of graphite and diamond which are allotropes of carbon. As can be seen with the example of carbon allotropes, certain physical properties can vary dramatically from allotrope to allotrope. As an example, CP titanium has a hexagonal close-packed (alpha) structure at room temperature that undergoes an allotropic transformation to a body-centered cubic (beta) structure at approximately 1650°F [900°C]. The beta structure will revert to an alpha structure upon cooling (at the transformation temperature). Alloying elements will change the transformation temperature.

alpha phase. The low-temperature allotrope of titanium with a hexagonal close-packed (HCP) crystal structure. The alpha phase promotes increased weldability and higher creep strength. Oxygen, nitrogen, and carbon are all alpha-stabilizing elements. Nitrogen and carbon are held to very low levels in modern titanium production. Oxygen (and iron) are the primary strengthening elements in the CP grades. These elements are held to lower levels in titanium filler metal. Most importantly, oxygen strengthens the final weld deposit, but the ductility of the weld deposit is decreased. Interestingly, these are the same elements we guard against introducing during welding.

alpha-beta grades or alloys. Most of the alpha-beta alloys are considered heat treatable with a wide range of possible properties and most can be welded. Their strength levels are medium to high but their creep strength is not as good as most alpha alloys. Their forming qualities are acceptable but generally exhibit a significant amount of spring-back.

alpha stabilizer. An alloying element that dissolves preferentially in the alpha phase and raises the alpha-beta transformation temperature. Typical alpha stabilizers include the elements of aluminum, carbon, nitrogen, oxygen, and tin, all of which increase the temperature at which the alpha phase is stable.

beta grades or alloys. The beta (β) or near-beta titanium alloys have a high percentage of beta-stabilizing elements, resulting in a microstructure that is metastable beta (a nonequilibrium state persisting for some period of time) after solution annealing. Beta stabilizers include molybdenum, vanadium, tungsten, silicon, tantalum, and zirconium. Extensive strengthening can occur by the precipitation of alpha (α) during aging. Postweld heat treatment (PWHT) is commonly applied to the beta alloys. The beta grades exhibit higher density, increased strain-rate sensitivity, and improved fabricability especially in the solution treated condition.

beta phase. The high-temperature allotrope of titanium with a body-centered cubic (BCC) crystal structure that occurs above the beta transus.

beta transus. The minimum temperature above which equilibrium alpha does not exist.

body-centered cubic (BCC). A unit cell that consists of atoms arranged at cube corners with one atom at the center of the cube (see Figure 3.1). This is the typical crystalline structure of the **beta phase** of titanium.

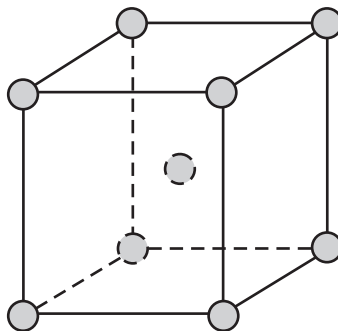


Figure 3.1—Body-Centered Cubic (BCC) Structure

commercially pure (CP). The mechanical properties of CP titanium are influenced by small additions of oxygen and iron. By careful control of these additions, the various grades of commercially pure titanium are produced to give properties suited to different applications. This alloy is readily weldable.

embrittled (or embrittlement). The severe loss of ductility and/or toughness of a material, usually a metal or alloy. For example, titanium can become embrittled when excess amounts of interstitial elements such as oxygen or nitrogen are introduced into the weld deposit due to inadequate welding practices.

hexagonal close-packed (HCP). A unit cell that consists of a hexagonal arrangement of atoms in a plane and surrounding an atom followed by three atoms in the next horizontal plane (see Figure 3.2). This last plane is offset from the initial plane atoms, followed by an identical planar location of atoms above this. If the first plane is A and the second B, then the repetitive arrangement of atom planes is A-B-A-B-A-B and so on. This is the typical crystalline structure of the **alpha phase** of titanium.

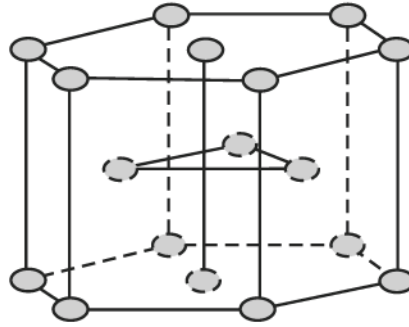


Figure 3.2—Hexagonal Close-Packed (HCP) Structure

interstitial elements. Those elements having relatively small atomic size so that they can assume positions in the interstices of the titanium lattice (see Figure 3.3). Common examples of interstitial elements are oxygen, hydrogen, nitrogen, and carbon.

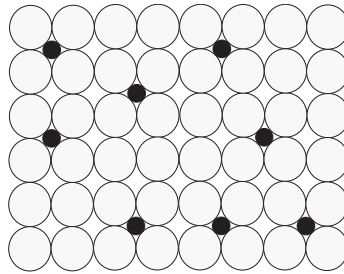


Figure 3.3—Interstitial Elements

M^2 . Pronounced M-squared, is a value used to quantify the quality of a laser beam and lets one know how tightly the beam can be focused. The lower an M^2 value, the better the laser can achieve beam-to-part coupling, and consistently obtain a desired weld result. The M^2 value is determined by dividing a measured laser beam output (product of waist diameter and divergence angle for a given wavelength), by that of an ideal Gaussian laser beam. The closer the M^2 value is to 1, the better its beam quality.

substitutional elements. To increase the strength of titanium metal and still maintain useful ductility, substitutional elements are employed. These elements replace titanium atoms in the lattice structure rather than situate in the voids between them (refer to Figure 3.4).

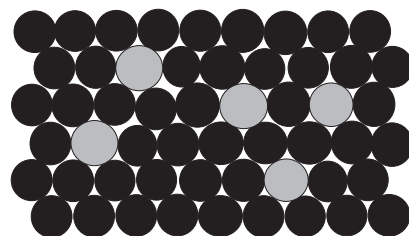


Figure 3.4—Substitutional Elements

Widmanstätten structure. A structure resulting from the formation of a new phase along certain crystallographic planes of the parent phase. This is also referred to as a “basketweave” structure in titanium and zirconium alloys. This structure will form in titanium material upon cooling from above the beta transus temperature. This structure can be seen in material hot worked or heat treated above the beta region or in a weld structure.

4. Introduction

Titanium and its alloys are used primarily in two areas of applications where the unique characteristics of these metals justify their selection. Corrosion-resistant applications typically utilize the low-strength, commercially pure grades. High-performance, weight-critical applications utilize high-strength titanium alloys that are typically processed to more stringent and costly requirements. However, as technical requirements in corrosive applications have become more severe, the use of high strength alloys with greater corrosion resistance (which include palladium and ruthenium additions) is increasing. Most titanium alloys can be fusion welded and all alloys can be welded by solid-state processes. Properly made welds in the as-welded condition are ductile and, in most environments, nearly as corrosion resistant as the base metal. However, improperly made welds can be severely embrittled or exhibit reduced corrosion resistance.

The equipment and techniques used in welding titanium are similar to those required for other high-performance materials such as stainless steels and nickel base alloys. However, titanium demands greater attention to cleanliness and to the use of auxiliary inert gas shielding. At temperatures of about 800°F [425°C] in air, the normal 40-Å [0.004 µm and/or 0.00016 mil] surface oxide increases in thickness by 2 to 3 orders of magnitude. Above about 1200°F [650°C], absorption leads to an increase in scale formation. In the molten state, oxygen and nitrogen are carried by convection throughout a weld and are then absorbed into the underlying titanium.

To prevent contamination from air, complete inert gas shielding of the face and root of the weld is required. Similarly, hot titanium reacts with and is embrittled by many materials, including organic and inorganic compounds and some metals. Hence, the parts to be welded must be meticulously cleaned of mill scale, oil and grease from machining operations, dust, dirt, moisture, and other potential contaminants.

The precautions necessary to maintain the required levels of cleanliness and shielding for successful titanium welding are discussed throughout this document. Many of the precautions may at first seem costly or unnecessary, especially for organizations that deal with titanium on an infrequent basis. However, it is important to remember that contamination of the weld has the potential to significantly increase the overall welding costs through the need for excessive weld repair, scrap, or reduced reliability in service. In this respect, the higher initial cost of establishing the proper procedures for titanium welding will result in significant savings over the production run through reduced scrap and rework and timely delivery of high-quality products.

4.1 Oxygen, Nitrogen, Carbon, and Iron in Titanium. A basic understanding of how titanium interacts with oxygen, nitrogen, carbon, and iron will help in understanding the importance of cleanliness and inert shielding in successful titanium welding.

Oxygen and iron are controlled in the production of titanium and are the primary strengthening elements in the unalloyed grades. Nitrogen and carbon in the filler metal are held to the lowest possible level, typically less than 25% of the specification maximums.

Unalloyed titanium gains its strength due to the presence of residual elements occupying sites between titanium atoms in the regular metal matrix. These elements are termed interstitial elements (as opposed to substitutional elements like iron that replace titanium atoms in the matrix) (see Figures 3.3 and 3.4). One way to visualize the effect is to imagine the oxygen intruding into the regular metal matrix, causing strain in the lattice. More oxygen leads to more strain. More lattice strain leads to greater hardness. A similar effect occurs in titanium alloys.

As an alloying element, iron has a mild strengthening effect, roughly 40% that of oxygen. Iron is a strong beta stabilizer. High iron will result in formation of an iron-rich secondary beta phase or TiFe compounds.

Unalloyed or commercially pure titanium is an “all-alpha” grade, which means its metal matrix has a hexagonal close-packed (HCP) structure at room temperature, as opposed to the body centered cubic (BCC) or “beta” structure of some alloys. Alpha alloys transform to a beta structure above the beta transus temperature, about 1600°F [870°C] for unalloyed titanium. Alpha grades do not respond to strengthening heat treatments, although they can be annealed or stress relieved.

4.2 Surface Oxide Film. When a clean or unoxidized titanium metal surface is exposed to air or any process stream or gas where any amount of oxygen is available, a complex titanium oxide layer forms (see Figures 4.1 and 4.2). The tightly adherent film consists of several distinct oxides: TiO_2 near the surface, Ti_2O_3 beneath, and TiO closest to the metal. Above 800°F [425°C], potentially detrimental oxides form at varying thicknesses depending on temperature and time. Depending on the specific application, such oxides may or may not require removal.

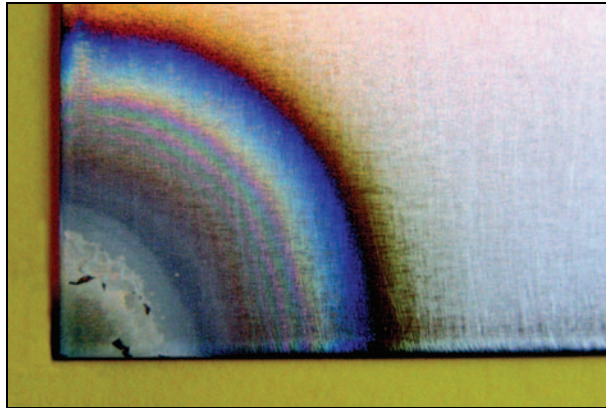
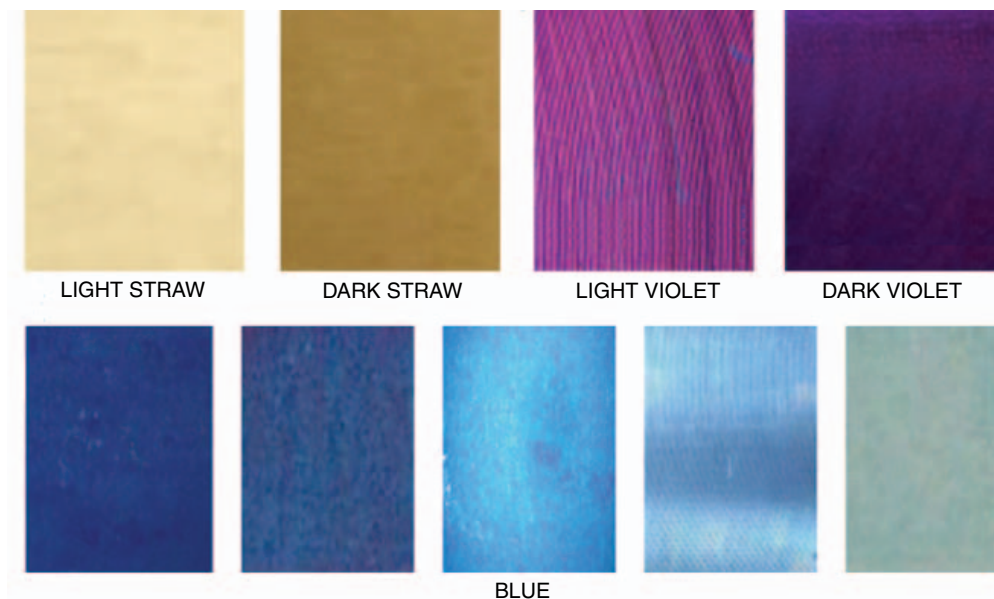


Image courtesy of MC Consulting

Notes:

- Figure 4.1 is a qualitative illustration of how discoloration varies with temperature. The lower left corner of the specimen reached the highest temperature and exhibits scale formation and gray discoloration evidenced by cracking and spalling of the thick oxide. As the distance increases from the heat source, the color varies until the blue, violet, and straw colors are present. Note that the color bands repeat. Most welding specifications only allow the presence of blue to straw discoloration and do not distinguish repetitive bands. The outermost band in this case is around 25 mm [1 in] radius from the corner of the specimen.
- Initial surface preparation: 150-grit emery followed by detergent wash and clean water rinse. The first color band is approximately 1.25 in [31 mm] in radius.

Figure 4.1—Titanium Surface Oxide Formed by Heating in Air



Note: These surface colors were produced by heating in an air atmosphere at low temperatures (light straw) to high temperatures (light blue).

Figure 4.2—Titanium Surface Color Contrast

5. Welding Processes

The practices described herein are limited to the gas metal arc, gas tungsten arc, laser beam welding, and plasma arc welding processes. These gas-shielded processes are well suited for joining titanium and titanium alloys, provided the gas shielding arrangement adequately protects the weld area from the atmosphere. All four of these processes can be performed using manual, semiautomatic, or automatic equipment in a chamber or an open-air environment with the use of auxiliary inert gas shielding. Other processes, including brazing, electron beam, friction, and resistance welding are also used on titanium and offer advantages for specific applications. Many of the principles discussed are applicable to all processes.

5.1 Gas Tungsten Arc Welding (GTAW). The GTAW process is the most commonly used joining process for titanium and its alloys. An arc between the tungsten electrode and base metal generates the heat for welding. Inert gas from the torch maintains the arc and protects the tungsten electrode and weld pool from atmospheric contamination. Welds can be made autogenously (i.e., without filler metal) or with the addition of wire.

GTAW can be performed in all positions and is the only process routinely used for orbital pipe welding of titanium. Higher-productivity variants of GTAW have been applied to titanium. The hot-wire GTAW process increases the deposition rate by preheating the wire, providing improved productivity for multipass welding of thicker sections. The keyhole GTAW and buried-arc GTAW processes achieve deeper penetration by operating at higher currents, allowing square butt joint welding of as much as 3/4 in [19 mm] thick titanium in one pass.

5.2 Gas Metal Arc Welding (GMAW). In GMAW, an arc is generated between a continuously fed filler wire and the base metal. The filler wire can also be considered a consumable electrode. Four methods of filler metal transfer are utilized with GMAW:

- (1) Short-circuit transfer
- (2) Globular transfer
- (3) Spray transfer
- (4) Pulsed-spray transfer

In titanium welding, spatter from the GMAW process is undesirable for many reasons, but primarily due to the likelihood of localized contamination as a result of hot spatter droplets coming into contact with the base metal, and those droplets then become dissolved into the weld pool. Because of this, short-circuit and globular transfer methods should never be used for welding titanium due to the large amounts of spatter they can generate. Spray transfer produces sufficient energy to fuse titanium; however, the preferred method of filler metal transfer is pulsed-spray, coupled to a push-pull weld gun capable of synchronizing wire feed with the pulsation waveform.

Weld gas is either argon or helium, or a mixture of the two. Good results have been obtained with 75% helium + 25% argon.

The GMAW process has the potential to produce a small amount of black soot on the base plate on either side of the weld bead. This soot should be removed between subsequent passes. As is common for welding titanium, the use of inert gas trailing and backing gas shielding is recommended and usually necessary.

Titanium weldments should be preferably positioned for flat and horizontal welding positions whenever practical. If overhead welding is necessary, it is particularly important to ensure that gas coverage is maintained on the face and root during welding.

Utilizing recent advancements in digital weld power source technology, GMAW of titanium is becoming a process of choice for thick-section welded assemblies. With deposition rates and travel speeds that exceed traditional GTAW by 10X or more, the GMAW process has the ability to consistently fuse the root of a fillet weld, and reduce the heat input into the weld area. The process provides an economical alternative for joining large structural components or equipment.

5.3 Plasma Arc Welding (PAW). Like the GTAW process, heat is transferred by an arc between a tungsten electrode and the base metal. However, the arc is constricted by a copper alloy orifice to form a highly collimated arc column. A portion of the shielding gas flows through the copper orifice to produce the characteristic plasma jet.

In the keyhole mode, the plasma jet fully penetrates the joint. Molten metal flows around the keyhole and behind the plasma jet as the torch traverses along the joint line. The process is operated with direct current, electrode negative, but a pulsed current can be used to broaden the tolerance window of welding parameters.

Because introduction of filler wire into the arc can cause instabilities in the gas plasma, keyhole PAW is normally performed autogenously using square butt joint preparation and will produce a small amount of underfill. The process offers productivity gains over conventional GTAW and GMAW.

Single-pass welds can be made in titanium from 1/16 in to 1/2 in [1.6 mm to 12.7 mm] thickness, but the process is limited to the flat and horizontal positions. A more detailed description of PAW can be found in AWS C5.1, *Recommended Practices for Plasma Arc Welding*.

5.4 Laser Beam Welding (LBW). Laser beam welding of titanium is a process that continues to find new applications as the technology matures, and for good reason. Due largely for its ability to deliver high-speed production, introduce low heat input that results in minimal HAZ, potential for high aspect ratio welds (depth to width), optics that can deliver a high power small diameter spot, pulse width and shaping capability, integration with precise and repeatable CNC motion control systems, and is a beam process that can be applied in the open air. When coupled with modern electronics and software it is a combination that makes for a robust titanium welding process.

Common to all metals, laser welding is applied in either keyhole or conduction welding modes. Keyhole welding produces high aspect ratio welds, typically greater than 1.5. A transverse cross section of a keyhole weld is anecdotally referred to as a nailhead because its appearance resembles that of a nail. Keyhole welding is used to achieve a deep penetrating weld. Conduction laser welding produces an elliptical transverse cross section and is used for shallow penetration welds often found in sheet metal welding.

The ability to successfully laser weld titanium still relies on the same basic principles that are required with common arc processes, those being: part cleanliness and proper inert gas shielding. However, there are additional factors that must be evaluated when considering a laser to process titanium:

(1) As most laser welds are autogenous, weld joint fit up is critical primarily because a small diameter spot lacks the ability to fill a large gap in a weld joint. Typically, a butt joint configuration adjoined tightly together is necessary. Lap and fillet joints are also possible, so long as the joint fit up remains tight. With a possible spot size <0.010 in [0.25 mm], a small amount of joint misalignment, excess gap, loose fixtures, or imprecise positioning equipment can result in poor coupling of the beam to the base metal or miss the weld joint entirely.

(2) The laser must have the capability to deliver a sufficiently high-power spot (power density), of the correct pulse width and shape, to couple with, and melt titanium.

Today, the most common commercially available laser welding system is the solid state, Nd:YAG fiber laser (1.06 μm wavelength). It can deliver a very high-quality beam ($M^2 < 2$) and can manipulate both the pulse width and shape. These features provide tremendous versatility when the delivery optics are coupled to a flexible fiber.

CO₂ lasers (10.6 μm wavelength) are also used for processing metals, but lack the ability to change the pulse shape as does the Nd:YAG. However, the CO₂ laser can produce a very high-energy pulse and therefore generate high peak power. Although they can weld some materials, these lasers are commonly found in cutting applications. Cutting titanium with a laser is best-performed using argon or helium gas assist. Even though it is less expensive, nitrogen is not desirable for cutting titanium. Although using Ar or He gases will help reduce the contamination layer along the cut edge, some aerospace specifications require further mechanical edge preparation to remove all remains of possible contamination.

Three conditions are necessary for a laser beam to effectively weld metal, those being: Sufficient power density, surface effects, and bulk effects:

(1) Power density is a measure of energy delivered to the surface of the metal for a given spot area, usually expressed as watts/in^2 [watts/cm^2]. Understandably, a tightly focused small diameter spot can deliver a greater power density than a large diameter spot. Power densities necessary to laser weld titanium can approach 10^8 watts/in^2 [1.55×10^7 watts/cm^2], depending on material configuration, thickness, and desired depth of penetration.

(2) Surface effect refers to the ability of the laser beam to couple to the surface of the metal. This ability to successfully couple the beam to base metal can be directly affected by the base metal surface finish, its oxide layer, cleanliness,