Chapter 1 : Introduction

This chapter introduces titanium and its alloys, discussing their application across various industries. It also includes the introduction of different welding processes utilised for the welding of titanium alloys, with a focus on pulsed gas tungsten arc welding, and discusses the major challenges that occur during the welding of titanium alloys. Finally, the importance of dissimilar welding of titanium alloys (especially CP-Ti/Ti-6Al-4V), and the major challenges that occur during dissimilar welding of titanium alloys have been discussed.

1.1 Titanium and its importance

Titanium is the ninth most abundant structural metal and the fourth most abundant metal on the earth's crust, exceeded by aluminium, iron and magnesium [1]. It is named after the Greek god The Titans, and it was first isolated by British mineralogist William Gregor from “Ilmenite ($FeTiO_3$)” in 1791. In 1795, a Berlin chemist named Martin Heinrich independently isolated titanium from “Rutile (TiO_2)” [2]. Thereafter, until centuries, not much contribution was made to extracting the titanium. In 1910, Matthew Albert Hunter, an American chemist, isolated the titanium from the heating of $TiCl_4$ with sodium in a steel bomb. Finally, in 1932, Wilhelm Justin Kroll produced a significant amount of titanium by combining $TiCl_4$ with calcium and became the father of the titanium industry. Initially, titanium is reduced to its carbide form from titanium ore, then converted into titanium chloride, and further, through a distillation and leaching sequence, forms titanium sponge, which is later processed into billets and poured into ingots. The American company DuPont was the first to produce titanium commercially in 1948, and the aerospace industry was the first consumer of titanium. Aerospace industries are still the prime consumer of titanium and its alloys [2, 3]. Figure 1.1 shows the uses of titanium in different parts of the GE-90 aero engine [1].

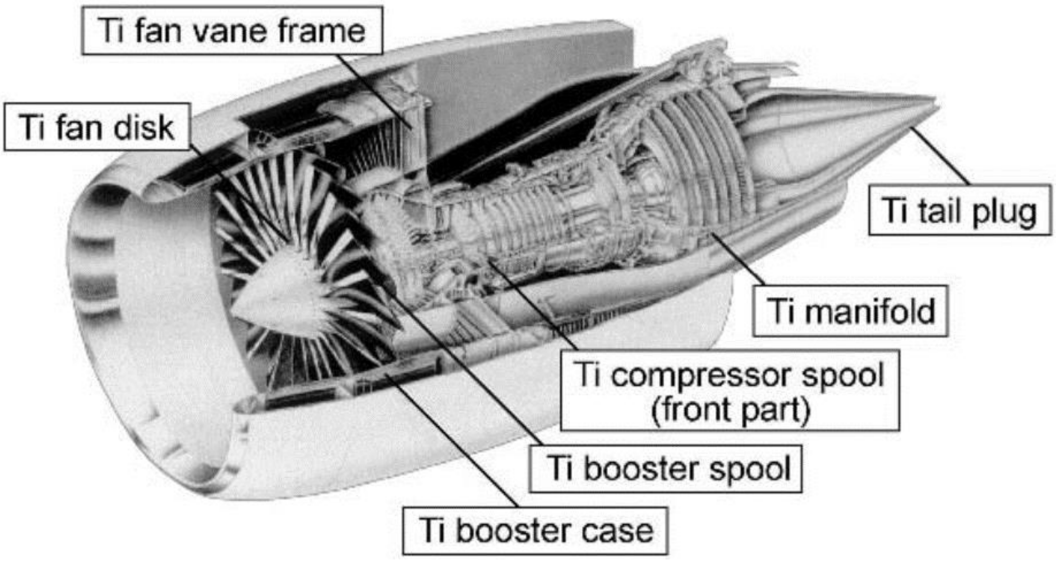

Figure 1.1 Titanium usage in the GE-90 aero-engine [1]

The right combination of high strength-to-weight ratio and outstanding corrosion resistance of titanium alloys, surpassing even steels, make them suitable for aerospace, biomedical, petrochemical, power generation, and chemical industries. Moreover, titanium's heat resistance allows it to maintain its strength and structure even at high temperatures, making it suitable for applications in gas turbines, heat exchangers, and other high-temperature environments. In recent years, titanium has also gained popularity in consumer products and design due to its aesthetic appeal, unique metallic lustre, and the ability to be anodized to produce a range of vibrant colours [1-4].

1.1.1 Properties of titanium

There are various ways to classify metals, such as ferrous or nonferrous metals, ingot or sintered metals, light or heavy metals. Figure 1.2 shows the density comparison of a few selected metals. The separation point between light and heavy metals is 5 gcm^{-}

^{3}. Therefore, titanium, with a density of 4.51 gcm^{-3} is the heaviest light metal and is classified as a nonferrous and light metal. Although it is two times heavier than the classic light metal aluminium, it has only about half the specific weight of iron or nickel [2, 5].

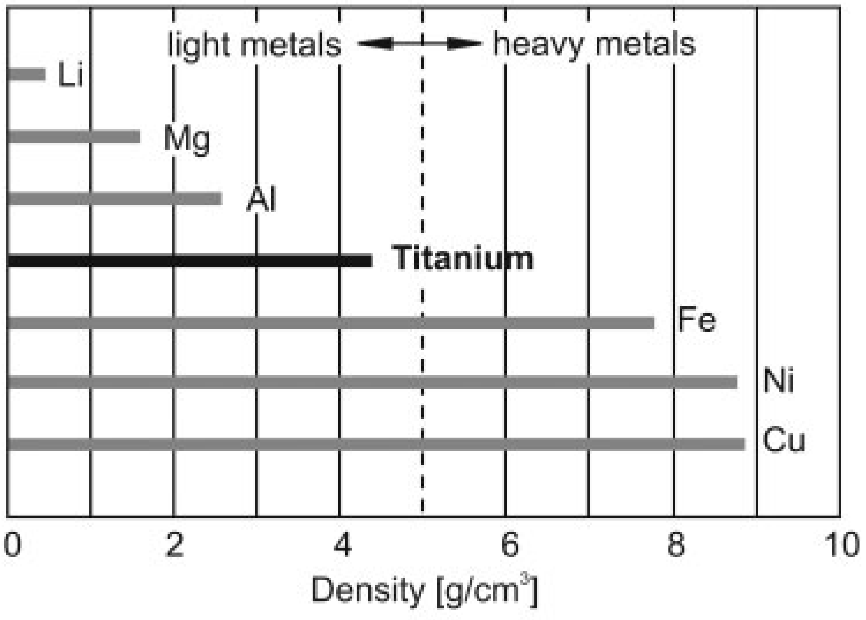

Figure 1.2 Density of some selected metals [2]

Some of the basic characteristics of titanium-based alloys are listed in Table 1.1 and compared to those of other structural metallic materials based on Fe, Ni, and Al. Although titanium alloys have the highest strength-to-weight ratio, however, their application is limited to specific areas due to its high price. This high price is mainly due to the high reactivity of titanium with oxygen, and an inert atmosphere or vacuum is needed during the production of titanium [3]. In contrast, titanium's high reactivity with oxygen causes the immediate formation of a stable and adherent oxide layer on its surface when exposed to air. This results in titanium's superior corrosion resistance in a wide range of aggressive environments, particularly in aqueous acidic conditions [2]. Titanium alloys, on the other hand, do not exhibit good corrosion resistance in sulfuric, hydrochloric, and phosphoric acids because they have a reducing environment. To improve corrosion resistance in these environments, noble metals or inhibitors (oxidising agents) are added to titanium alloys [3]. Titanium has a much higher melting temperature compared to aluminium, its main competitor in lightweight structural applications. This characteristic gives titanium a significant advantage at application temperatures exceeding 150°C. Titanium alloys can be used up to 600 °C with good resistance to creep and oxidation, and they retain their toughness even at liquid nitrogen temperatures. Beyond 600 °C, the rapid diffusion of oxygen through the oxide surface layer leads to excessive growth of the oxide layer and the embrittlement of the adjacent oxygen-rich layer in the titanium alloy. This combination of lightweight, strength, corrosion resistance, high melting point, and biocompatibility makes titanium an extraordinary material that meets the demands of advanced technological applications [1, 6].

Table 1.1 Some important characteristics of titanium-based alloys and comparison with other structural metallic materials based on Fe, Ni, and Al [1]

Key Properties	**Ti**	**Fe**	**Ni**	**Al**
Melting Temperature (°C)	1670	1538	1455	660
Allotropic Transformation (°C)	β→α (at 882 °C)	γ→α (at 912 °C)	-	-
Crystal Structure	bcc → hex	fcc → bcc	fcc	fcc
Room Temperature E (GPa)	115	215	200	72
Yield Stress Level (MPa)	1000	1000	1000	500
Density (g/cm3)	4.5	7.9	7.9	2.7
Comparative Corrosion Resistance	Very High	Low	Medium	High
Comparative Reactivity with Oxygen	Very High	Low	Low	High
Comparative Price of Metal	Very High	Low	High	Medium

1.1.2 Alloys of titanium

Similar to iron and cobalt, titanium also shows allotropic transformation in two crystallographic forms, it exits in hexagonal close pack (hcp) structure at room temperature, known as α-phase, which transforms to body centred cubic (bcc) above β-transus temperature, known as β-phase. The β-transus temperature for pure titanium is around 882 °C, and it varies with the addition of α and β stabilizers [3]. Figure 1.3 (a) shows the crystal structure of hcp (α-phase) with its lattice parameters. It also indicates one of the three most densely packed (0002) planes, known as basal planes, along with one of the three planes, referred to as prismatic planes, and one of the six planes, known as pyramidal planes, as well as the close-packed directions a1, a2, and a3 with the indices <1120>. Figure 1.3 (b) illustrates the unit cell of the bcc (β-phase) with its lattice parameter value of pure β titanium at 900°C (a = 0.332 nm). It also indicates one variant of the six most densely packed lattice planes and shows the close-packed directions, corresponding to the four <111> directions [1, 2, 7].

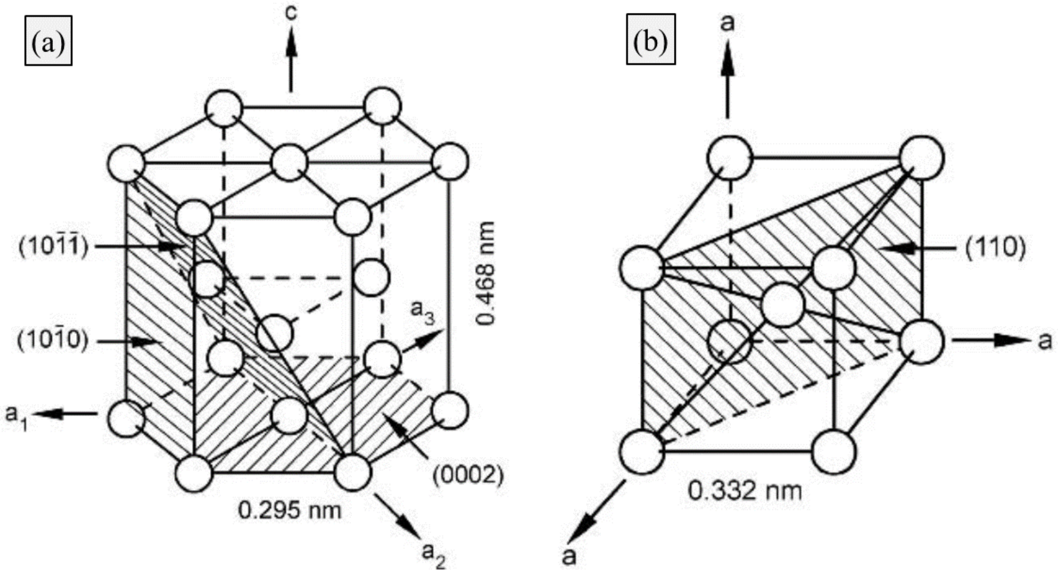

Figure 1.3 Crytal structure of: (a) hcp (α-phase); (b) bcc (β-phase) [1]

To improve mechanical properties and stabilize the phases, alloying elements are added to pure titanium. Titanium alloys are categorized based on the percentage of these elements added and according to the microstructure of the alloys [8]. These elements can be α-stabilizers, β-stabilizers, or neutral elements. Al, Zr, Sn and O are a few α stabilizers element, and equivalent of α stabilizers is given using $[Al]_{equivalent}$. Similarly, Mo, V, Ta, Nb, Fe, Mn, Cr, Si, and H are β stabilizers, and the equivalent of β stabilizers is given using $[Mo]_{equivalent}$. Equation 1.1 and 1.2 represent the $[Al]_{equivalent}$ and $[Mo]_{equivalent}$ [1]. Figure 1.4 shows the effect of alloying elements on the phase diagrams of titanium alloys. β stabilizers form either an isomorphous or eutectoid system, depending on the alloying element. Isomorphous systems are important due to the high solubility of β-stabilizers and the low chances of formation of intermetallic compounds. The α-stabilizing elements extend the α-phase field to higher temperatures, while the β-stabilizing elements shift the β phase field to lower temperatures [1, 2]. Aluminium is among the most crucial alloying elements due to its potent solid solution strengthening capabilities and density reduction, which is why it is found in virtually all titanium alloys. Molybdenum and vanadium are the two most popular β-stabilizing additives, providing strength to the β-phase. Eutectoid group elements lower the β-transus temperature as low as 330 °C below the unalloyed transformation temperature. β-alloys are age-hardened alloys. Hardness can be varied by ageing by controlling the amount of α-phase and forming intermediate phases (e.g., ω-phase and $TiCr_2$) [3]. Tin and zirconium are unique in that they neither stabilise the α-phase nor the β-phase in the crystal structure, however, they do contribute to the solid solution strengthening of the α-phase. Tin is also recognized for its ability to enhance weldability. Oxygen and nitrogen act as potent α-stabilizers, while iron stands out as the most effective β-stabilizer. The higher the contents of oxygen and nitrogen, the greater the strength, but reducing the content of oxygen, nitrogen, and aluminium will enhance ductility, fracture toughness, stress-corrosion resistance, and resistance to crack growth in the material [1].

$$[Al]_{equivalent} = [Al] + 0.17[Zr] + 0.33[Sn] + 10[O] \quad \text{Eq. 1.1}$$

$$[Mo]_{equivalent} = [Mo] + 0.2[Ta] + 0.28[Nb] + 0.4[W] + 0.67[V] + 2.5[Fe] + 1.25[Cr] + 1.7[Mn] \quad \text{Eq. 1.2}$$

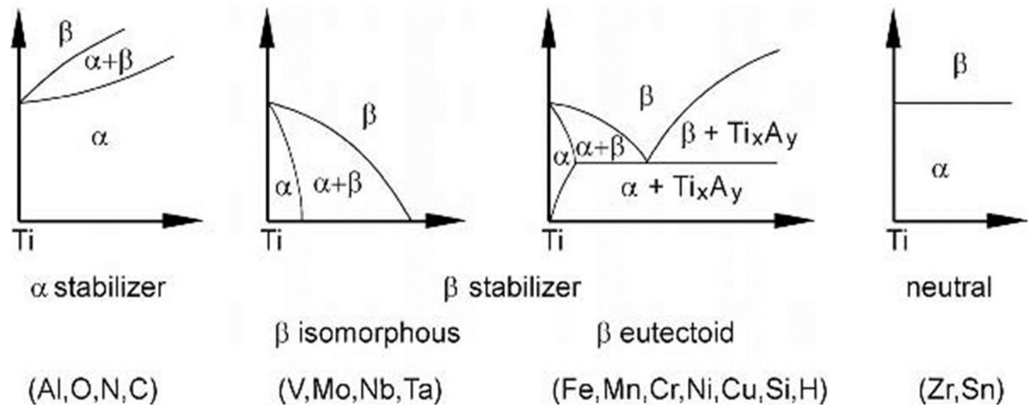

Figure 1.4 Effect of alloying elements on phase diagrams of titanium alloys (schematically) [1]

The titanium alloys are classified as α-alloys, near α alloys, (α+β) alloys, metastable β alloys, and β alloys depending upon the different phases and of amount phases present. Generally, α alloys are the pure form of titanium alloys and are mildly alloyed with neutral elements or α-stabilizers. Near α alloys contain less than 2 wt.% β-stabilizers and less than 10 vol.% β-phase. (α+β) alloys contain 4-6 wt.% β-stabilizers and 10-40 vol.% β-phase. Near-β or metastable β alloys contain 10-15 wt.% β-stabilizers and less than 50 vol.% β-phase. Lastly, β alloys contain approximately 30 wt.% β-stabilizers, but these alloys are not commercial [1]. Each group of titanium alloys has different characteristics and has a number of different titanium alloys. Figure 1.5 shows the flow diagram of the important characteristics of different titanium alloy families and a few important examples of each group. This flow diagram has been drawn by keeping Ti-6Al-4V in the centre, and variation in different characteristics has been shown in it. For example, weldability increases towards α and near-α titanium alloys and decreases towards highly β-stabilized titanium alloys, which become embrittles during welding. Similarly, heat treatment capacity increases towards β-alloys and decreases towards α-alloys due to the absence of a secondary phase [3].

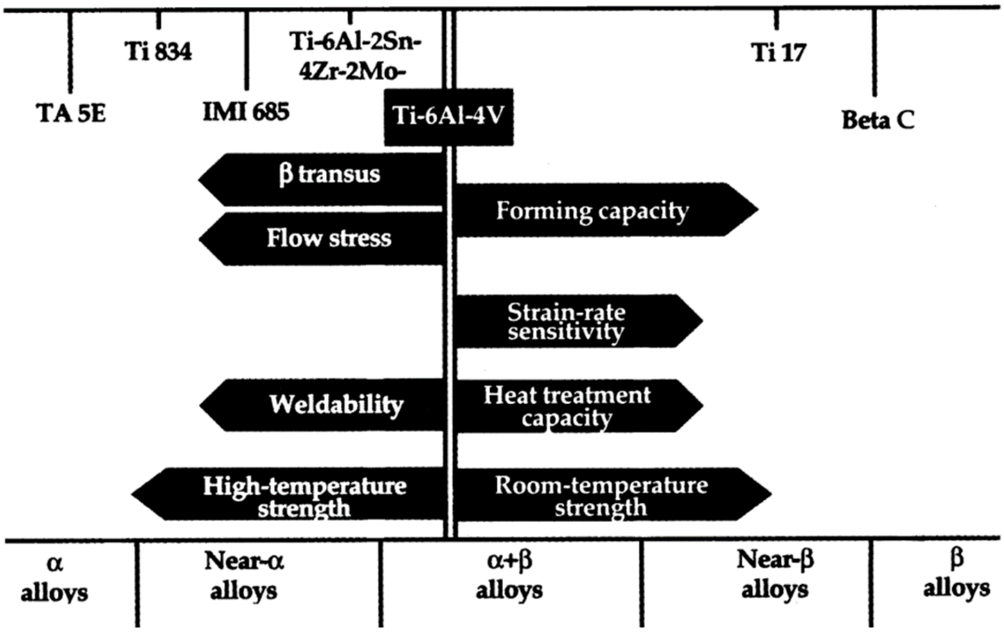

Figure 1.5 Main characteristics of different titanium alloy family groupings [3]

A few important commercial titanium alloys are listed in Table 1.2. The group of alloys called α alloys consists of the various grades of CP titanium and α alloys. The four different grades of CP titanium differ with respect to their oxygen content from 0.18% (grade 1) to 0.40% (grade 4) in order to increase the yield stress level. Depending on the amount of β-phase stabilizers, a mixture of α and β phases appears at room temperature, also known as (α+β) alloys. These alloys have higher strength and respond well to heat treatment, but they are less formable than alpha alloys. This group of alloys is frequently used in titanium alloys, with Ti-6Al-4V (Grade 5) titanium alloy being highly popular. Another group of titanium alloys is known as β-alloys, which contain a large amount of β-phase stabilisers [1]. The high concentration of alloying elements makes β alloys the densest among the groups of titanium alloys. At room temperature, β-alloys have similar strength to α and (α+β) alloys, but they are more formable. However, their ability to retain high temperature strength is poor. They can be hardened to much higher yield stress levels than (α+β) alloys. They are especially effective in environments where hydrogen absorption is possible because the β phase has a higher hydrogen tolerance than the α phase [2, 3].

Table 1.2 List of important commercial titanium alloys [1]

Common Name	**Alloy Composition (wt%)**	**T_β (°C)**
α Alloys and CP Titanium		
Grade 1	CP-Ti (0.2Fe, 0.18O)	890
Grade 2	CP-Ti (0.3Fe, 0.25O)	915
Grade 3	CP-Ti (0.3Fe, 0.35O)	920
Grade 4	CP-Ti (0.5Fe, 0.40O)	950
Grade 7	Ti-0.2Pd	915
Grade 12	Ti-0.3Mo-0.8Ni	880
Ti-5-2.5	Ti-5Al-2.5Sn	1040
α+β Alloys		
Ti-811	Ti-8Al-1V-1Mo	1040
IMI 685	Ti-6Al-5Zr-0.5Mo-0.25Si	1020
Ti-6242	Ti-6Al-2Sn-4Zr-2Mo-0.1Si	995
Ti-6-4 (Grade 5)	Ti-6Al-4V (0.20O)	995
Ti-6-4 ELI	Ti-6Al-4V (0.13O)	975
Ti-662	Ti-6Al-6V-2Sn	945
IMI 550	Ti-4Al-2Sn-4Mo-0.5Si	975
β Alloys		
Ti-6246	Ti-6Al-2Sn-4Zr-6Mo	940
Ti-17	Ti-5Al-2Sn-2Zr-4Mo-4Cr	890
Ti-10-2-3	Ti-10V-2Fe-3Al	800
Beta 21S	Ti-15Mo-2.7Nb-3Al-0.2Si	810
Ti-LCB	Ti-4.5Fe-6.8Mo-1.5Al	810
Ti-15-3	Ti-15V-3Cr-3Al-3Sn	760
Beta C	Ti-3Al-8V-6Cr-4Mo-4Zr	730

Among all the α-alloys, grade 2 (CP-Ti (0.3Fe, 0.25O)) is very popular due to its excellent formability, higher corrosion resistance, good impact toughness, good stress corrosion cracking, and being cheaper than other α titanium alloys [2]. The combination of these properties makes CP-Ti (Grade 2) titanium a strong candidate for a wide range of applications in industries such as chemical, marine, aerospace, and medical. Similar to α-alloys, Ti-6-4 (Ti-6Al-4V (grade 5)) is also very popular in α+β titanium alloys, capturing around 67% of the market share [1]. It has replaced the use of many conventional titanium alloys since its inception. The addition of aluminium stabilises and strengthens the α phase, increases α+β↔β transformation temperature, and reduces alloy density. The addition of vanadium stabilises β-phase, reduces α+β↔β transformation temperature, and facilitates hot working (higher volume fraction of β-phase) [9]. Depending on the required mechanical properties, heat treatment can be applied to the Ti-6Al-4V alloy. The Ti-6Al-4V alloy contains approximately 15 vol% β-phase at 800°C in equilibrium. This alloy exhibits an exceptionally good balance of strength, ductility, fatigue resistance, and fracture properties. It is the most frequently used titanium alloy due to its good formability, ease of workability, excellent castability, and exceptional weldability. The extra-low interstitial (ELI) version of this popular alloy demonstrates particularly high fracture toughness values and excellent damage tolerance properties. The key properties of both CP-Ti (grade 2) and Ti-6Al-4V (grade 5) have been listed in Table 1.3 [5].

Table 1.3 Key properties of CP-Ti (grade 2) and Ti-6Al-4V (grade 5) [5]

Properties	**CP-Ti (grade 2)**	**Ti-6Al-4V (grade 5)**
Melting Point	1665 °C	1604-1660 ˚C
Beta Transus Temperature	913 °C	980 ˚C
Density	4.51 g/cm^3	4.43 g/cm^3
Ultimate Tensile strength	344-420 MPa	950 MPa
Yield Tensile Strength	275-410 MPa	880 MPa
Modulus of elasticity	105 GPa	113.8 GPa
Hardness, Vickers	145	349
Shear modulus	45 GPa	44 GPa
Poisson’s ratio	0.37	0.31
Thermal conductivity	16.4 W/m K	6.7 W/m ˚C
Specific Heat Capacity	523 J/kg ˚C	526 J/kg ˚C

1.1.3 Applications of titanium alloys

Titanium alloys have widespread applications across a spectrum of different industries due to their exceptional properties. The application of these alloys depends on the selective properties of the different groups of titanium alloys as well as the demand for these properties by different industries. These alloys are highly demanded due to their excellent combination of high strength-to-weight ratio, extended fatigue life, toughness, excellent corrosion resistance, and good fatigue properties, which make them suitable for numerous chemical, marine, military, and aerospace applications. The advancement in titanium metallurgy has further bolstered its reach, particularly with the successful resolution of issues related to titanium alloy welding [3]. Typically, low-strength unalloyed commercially pure (CP) titanium is utilised in fabricating tanks, heat exchanger tubes, and reactor vessels for chemical processing, desalination, and power generation plants. A few important applications of CP-Ti (grade 2) in tube and frame heat exchangers, complex-shaped parts of heat exchangers, and components for marine and chemical processing operations are shown in Figure 1.6 [1, 2]. The (α+β) titanium alloys group is most popular for their biocompatibility and application in developing prosthetic femoral components and surgical instruments. Their uses are not limited to biomedical applications but are also used in fabricating connecting rods, intake valves, movable turbocharger vanes, pistons, etc. A very popular (α+β) titanium alloy, Ti-6Al-4V, is currently the most widely used titanium alloy, constituting over 50% of global titanium tonnage. Its dominance remains unchallenged due to its ability to vary mechanical and physical properties by controlling microstructure development during thermomechanical processing. A few important applications of Ti-6Al-4V in the casting of a Bell Helicopter transmission adapter case, a large steam turbine rotor, and large steam turbine blades are shown in Figure 1.7 [2]. Beta titanium alloys have very limited applications, and despite being the costliest among other titanium alloy groups, they have a minimal market share. Only a few applications of beta titanium alloys include the landing gears of aeroplanes, truck beams, and surgical implants. While the aerospace industry accounts for over 80% of titanium alloy usage, titanium alloys are also prevalent in medical prostheses, chemical processing, marine applications, automotive components, and sporting equipment[2].

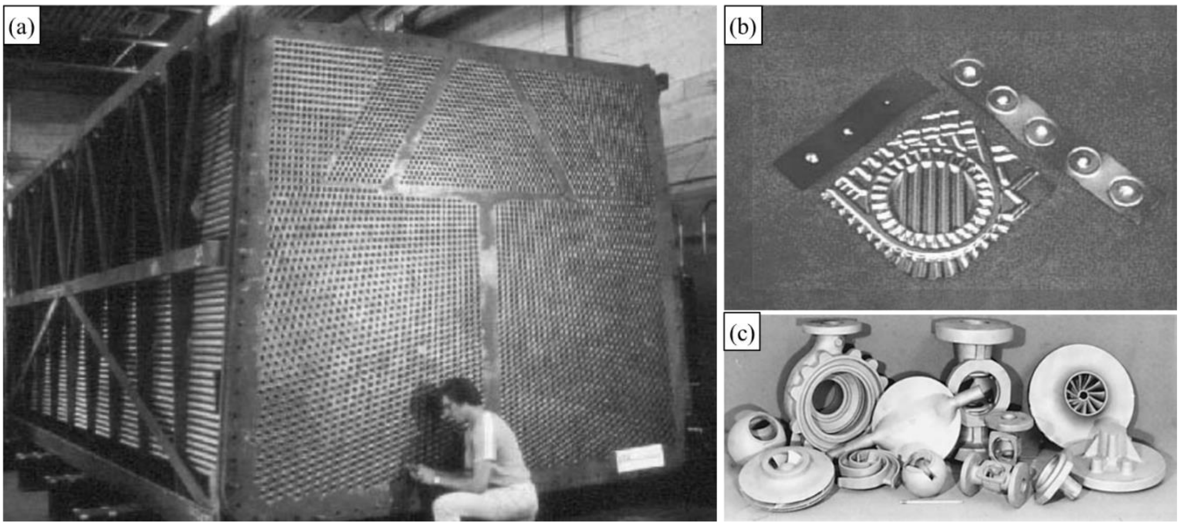

Figure 1.6 Applications of CP-Ti: (a) tube and frame heat exchanger; (b) complex shaped parts of heat exchanger; (c) components for marine and chemical processing operations [1, 2]

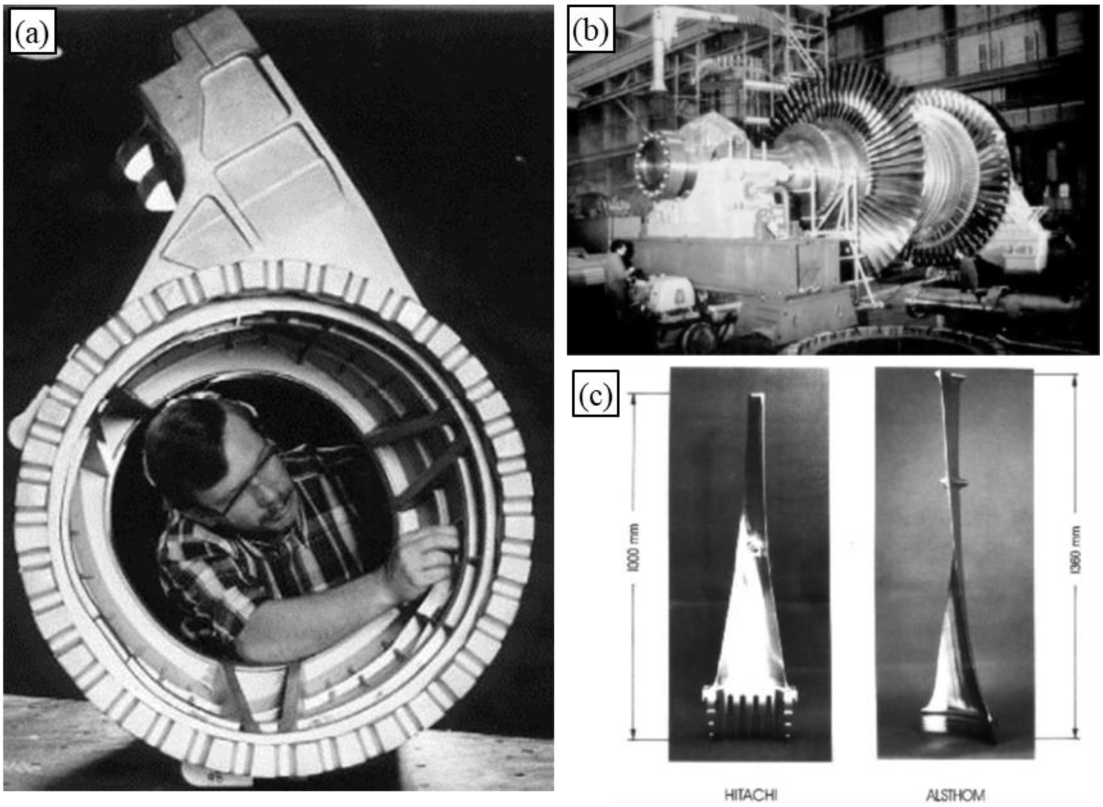

Figure 1.7 Applications of Ti-6Al-4V: (a) casting of a Bell Helicopter transmission adapter case; (b) large steam turbine rotor; (c) Large steam turbine blades [2]

1.2 Welding process and its importance in fabrication

The process of permanently joining two workpieces is known as welding, and it falls into two main categories:

1. Autogenous welding: when welding is performed by the direct melting of joining materials.
2. Non-autogenous (using filler wire welding): when an additional filler material is supplied during welding.

Besides choosing the right alloy, an important aspect of the manufacturing process is selecting the method for joining pieces of material. Welding can produce components that are lighter and have better cost and structural integrity than other methods, such as riveting [10]. The welding process can also be classified by the nature and intensity of the heat source used. Broadly, it can be classified as fusion welding and solid-state welding processes [11].

1.2.1 Fusion and solid-state welding processes

Fusion and solid-state welding are two fundamental categories of welding processes, each with distinct characteristics and applications. Fusion welding methods, such as arc welding, laser beam welding (LBW), and electron beam welding (EBW), involve the melting and fusion of base materials, and sometimes filler metals are needed to create a strong joint. These processes are widely used in industries like construction, automotive, and shipbuilding due to their versatility and ability to join a wide range of materials, including metals and thermoplastics, without any external pressure. On the other hand, solid-state welding techniques, such as friction welding, ultrasonic welding, and diffusion bonding, do not involve melting the materials. Instead, they rely on applying heat and pressure to create bonds between the materials at the atomic level, resulting in joints with excellent mechanical properties and often no need for filler metals. Solid-state welding processes are preferred for joining dissimilar materials, heat-sensitive alloys, and materials prone to distortion or metallurgical changes during fusion welding [12].

Each type of welding process has its advantages and limitations. The welding processes are selected based on factors such as material properties, joint requirements, production efficiency, and cost considerations. Fusion welding processes excel in versatility and speed, while solid-state welding offers advantages in joint quality, material compatibility, and heat-affected zone control. Solid welding processes limit the complexity of weld joints, material strength and welding thin sheets; however, fusion welding processes work satisfactorily in such complex situations [13]. Titanium alloys are best welded using fusion welding processes, and low-cost gas tungsten arc welding (GTAW) and its variants are good options for welding titanium alloys, provided that the effects of process parameters are thoroughly understood and precisely optimized, and the weldment is protected from atmospheric contamination. Continued research and development in GTAW is essential to meet evolving industry demands for reliable, high-performance joints across various manufacturing sectors [14].

1.2.2 Gas tungsten arc welding (GTAW) process

Gas tungsten arc welding (GTAW), sometimes referred to as tungsten inert gas (TIG) welding, is a non-pressure fusion welding process. In this process, the coalescence of metals is produced using a high-energy density arc between the base metal and a non-consumable tungsten electrode. The weld pool area is protected from the atmosphere and other possible contamination by shielding provided using an inert gas or mixture of inert gases. Typically, helium, argon, or a combination of these two are used for shielding purposes. Welds prepared using GTAW have a much better surface appearance and require little or no finishing operation, as no spatter is created in this process. It is a very clean welding process that produces high-quality, reliable joints, and almost all metals can be welded using this process. Due to the cleanliness of this process, reactive metals like titanium and zirconium can be easily welded. This process can be used for autogenous (without filler metal) welding as well as non-autogenous (using filler metal) welding [8]. The schematic of the GTAW setup is shown in Figure 1.8 [15].

The advantages of using the GTAW process include a stable arc, ductile welds, and excellent control over heat input [8, 14]. GTAW has a few limitations, including a low deposition rate, a slow process, and the inability to weld thick plates in a single pass. The GTAW process necessitates the external supply of filler material, which requires skilled workers for manual operation. Depending on the thickness of the sheets being welded, welding using GTAW can be carried out with or without filler metal [14]. Joint preparation and filler materials are needed for the welding of sheets with thicknesses greater than 3 mm; however, sheets with thicknesses up to 3 mm can be autogenously welded [16, 17]. Using some modifications, GTAW and its variants can be extensively used for the large thickness sheets and welding of dissimilar alloys [8, 14].

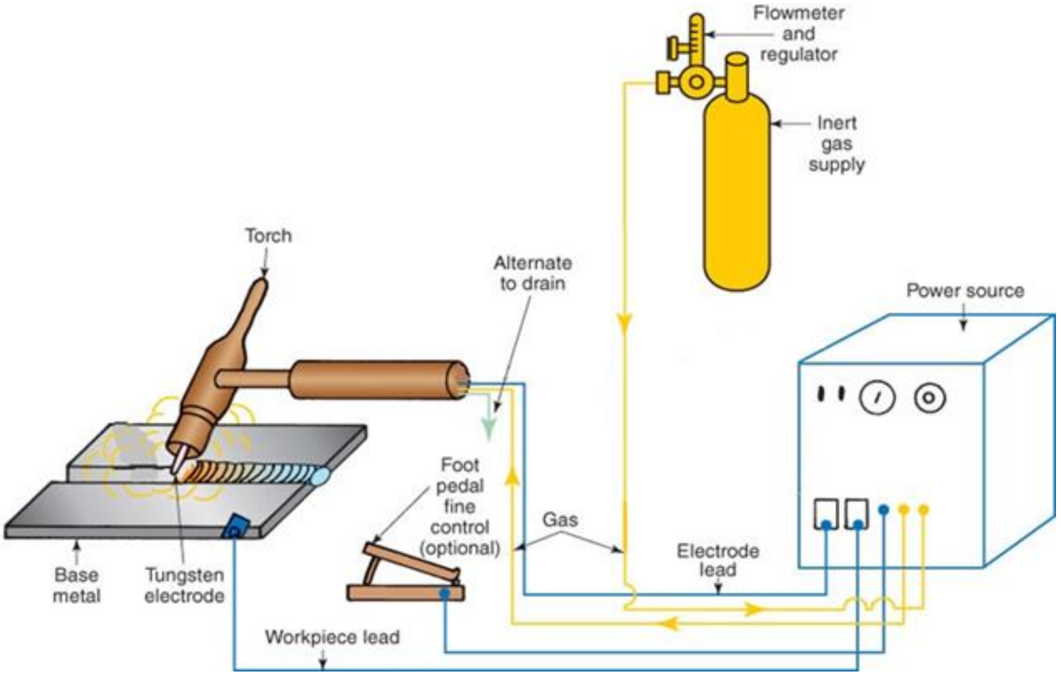

Figure 1.8 Schematic of GTAW set-up [15]

1.2.2.1 Equipment for GTAW process

The various equipment utilized for the GTAW process are shown and labelled in Figure 1.8, and some important equipment, including power source, welding torch construction, non-consumable tungsten electrodes, and shielding gas have been discussed in subsequent sections.

Power source

The power source required to maintain the GTAW arc has a drooping or constant current characteristic, which provides an essentially constant current output when the arc length is varied over several millimetres. Therefore, the natural variations in arc length that occur in manual welding have little effect on welding current. The capacity to limit the current to the set value is equally crucial when the electrode is short-circuited to the workpiece; otherwise, excessively high current will flow and damage the electrode and workpiece. The open-circuit voltage of the power source ranges from 60 to 80 V [14].

GTAW Welding torch construction

GTAW welding torch is designed for either automatic or manual operation and is equipped with cooling systems using air or water. The automatic and manual torch is similar in construction, but the manual torch has a handle while the automatic torch normally comes with a mounting rack. Figure 1.9 shows the schematic of an exploded view of key components of the manual GTAW torch [11]. The key components are also labelled in the figure. The torch is connected with cables to the power supply and with hoses to the shielding gas source and water supply. The internal parts of a torch are made of hard alloys of copper or brass so that they can transmit heat and current effectively and have better wear resistance. The collet is sized according to the diameter of the tungsten electrode it holds. The nozzle is very immediate to the arc and exposed to high temperatures; therefore, the nozzle is made up of refractory materials like ceramics or fused quartz, which can withstand high temperatures without any damage. The collet body is used to diffuse the shielding gas over the electrode; it is sometimes replaced with the gas lens to improve the shielding by creating a laminar flow of shielding gas over the tungsten electrode and arc. The body of the torch, including the cap and handle, is made of heat-resistant insulating plastic, covering the metallic components and providing insulation from heat and electricity to protect the welder’s health [9, 14].

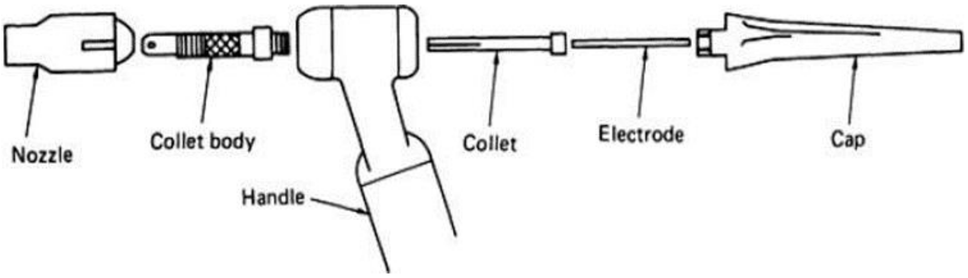

Figure 1.9 Schematic of an exploded view of the GTAW torch [11]

Electrodes

The non-consumable tungsten electrodes are used in the GTAW process. Tungsten has a very high melting temperature (3422 °C), excellent operating characteristics and good stability [18]. Tungsten electrodes are classified on the basis of their chemical composition. For better recognition, the tip of the electrode has different colour coding. Table 1.4 shows the classification of selected tungsten electrodes for GTAW with their composition and colour coding [14]. Pure tungsten electrodes are primarily used during GTAW in alternating current (AC) mode and have the highest consumption rate. Sometimes radioactive alloys are doped in the form of their oxides in the tungsten electrodes for easy arc initiation. For example, 2% thoria (ThO2) is added to the most common GTAW electrode, also known as thoriated (EWTh-2). These electrodes have the best starting characteristics. The arc can be started and maintained at a lower voltage, which is suitable for direct current (DC). The easy arc initiation of the thoriated electrode is a result of the lower work function of thorium, which allows it to emit electrodes readily at a lower voltage. However, thorium is a radioactive element, so care must be taken during the grinding of these electrodes.

The grinding waste is considered hazardous; therefore, disposal may be subject to environmental regulations. Some countries have banned radioactive-based tungsten electrodes and replaced them with rare earth metal and lanthanoid-based tungsten electrodes. Lanthanated (EWLa-1) tungsten electrodes have similar arc initiation characteristics as thoriated electrode and can be used with AC/DC currents. Ceriated (EWCe-2) tungsten electrodes are slightly better than thoriated tungsten electrodes with respect to arc initiation and melt-off rate. Zirconium doped zirconated tungsten electrodes are used in AC mode [12, 14].

Table 1.4 Classification of selected tungsten electrodes for GTAW with their composition

AWS classification	**Colour**	**Alloying Element**	**Alloying Oxide**	**Alloying Oxide wt.%**
EWP	Green	-	-	-
EWCE-2	Orange	Cerium	$CeO2$	2
EWLA-1	Black	Lanthanum	$La2O3$	1
EWTH-1	Yellow	Thorium	$ThO2$	1
EWTH-2	Red	Thorium	$ThO2$	2
EWZR-1	Brown	Zirconium	$ZrO2$	0.25
EWG	Grey	Not Specified	-	-

The shape of the electrode tip can affect the resulting weld shape. Electrodes with included angles from 30° to 90° give a stable arc and good weld penetration (high depth-to-width ratios). Electrodes with smaller included angles (5° to 30°) are used for grooved weld joints to eliminate arcing to the part side walls [19].

Shielding gases

Shielding gases in GTAW helps in stabilizing the arc and displacing atmospheric gases from the weld region to protect the weldment from atmospheric contamination. Reactive metals like titanium react with atmospheric gases such as nitrogen and oxygen and form very stable oxides and nitrites. Excessive contamination from atmospheric gases may cause embrittlement in the weld. The selection of a shielding gas depends on several factors, including the type of material being welded, joint design, and desired final weld appearance. The effect of different shielding gases on weld pool shape has been shown in Figure 1.10 [12]. Argon, being non-reactive and heavier than atmospheric gases, can effectively replace them and provide better shielding during the welding of reactive metals. Sometimes, pure helium or a mixture of helium and argon is used during GTAW to achieve higher penetration. The work function of helium (24 eV) is almost double that of argon (15.7 eV), resulting in high heat input at the anode (workpiece). This is because the heat absorbed as work function at the cathode (tungsten electrode) is recovered as heat at the anode after the electrons recombine. However, due to the higher thermal conductivity and lower density of helium gas, a broader and shallower weld pool is observed using helium gas, when compared to argon gas, where deeper and narrower welds are observed. To take advantage of both high heat input and lower thermal conductivity, mixtures of He and Ar are used [12]. Usually, CO_2 gas is not used in the GTAW process due to its reactivity, instability, and the superior performance of inert gases like argon and helium in providing high-quality welds. Along with the shielding gas type, the purity and flow rate are also important considerations during the welding of reactive metals. High purity (99.99%.) shielding gas and a high flow rate of shielding gas are required during the welding of titanium alloys [11, 12].

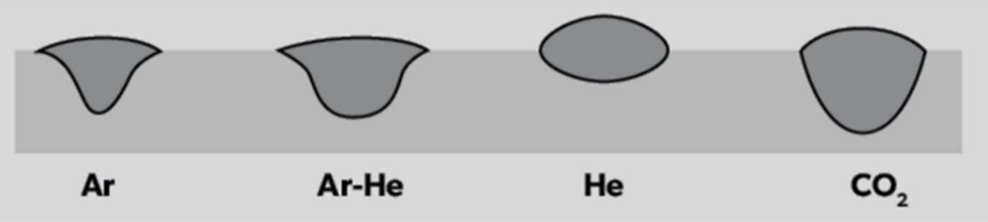

Figure 1.10 Effect of different shielding gases on weld pool shape [6]

1.2.2.2 Pulsed current GTAW (pulsed-GTAW)

Pulsed-GTAW is a modified version of the GTAW process in which welding current alternates between a low-level background current (I_b) and a high-level peak level (I_p) after a fixed interval of time. Pulsed current characteristics during the pulsed GTAW process are shown in Figure 1.11 [14]. Where T_p and T_b are the times for peak current and background current, respectively. In current pulsing, melting takes place during peak current, and solidification takes place during background current. This allows arc energy to be efficiently utilized to fuse a spot of controlled dimensions in a short time, creating the weld as a series of overlapping nuggets known as ripples. This intermittent melting and solidification using pulse current led to refinement in the fusion zone and HAZ grain size and improvement in the sub-structural mechanical properties. Current pulsing also helps to reduce the width of the HAZ and weld zones. A rectangular pulse is generally suitable for most of the purposes; however, if necessary, a pulse of other (triangular and sinusoidal) shapes can be generated to achieve the desired objective. The heat input in a rectangular pulse is calculated using the mean current. Equation 1.3 uses the weighted average of peak current and background current to calculate the mean current in pulsed-GTAW. The value of heat input is calculated using Equation 1.4, where the value of constant current is replaced by the mean current during pulsed-GTAW [11, 14].

$$I_m = \frac{I_p t_p + I_b t_b}{t_p + t_b} \qquad \text{Eq. 1.3}$$

$$H = \frac{I_m \times V}{v} \qquad \text{Eq. 1.4}$$

Where,

H = Heat input (J/mm)

I_m = Mean Current (Amp)
V = Voltage (V)
v = Velocity (mm/sec)

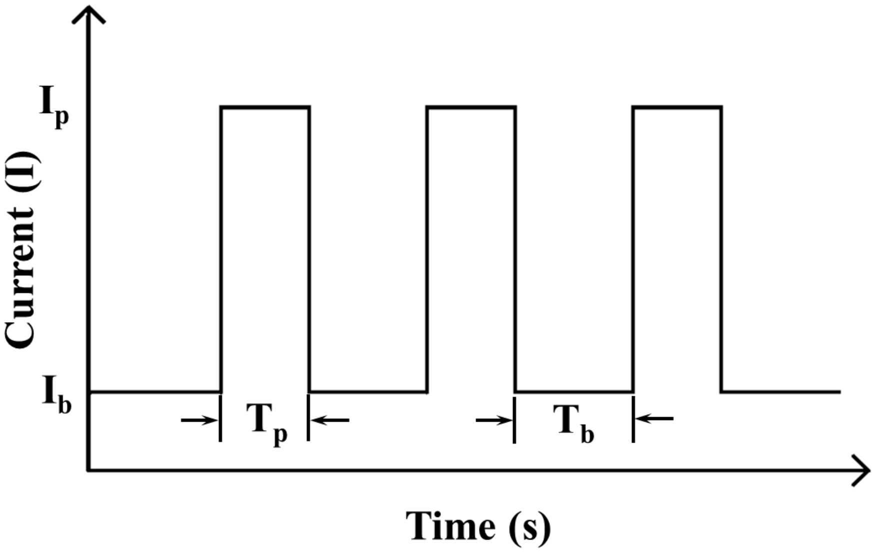

Figure 1.11 Pulsed current characteristics during pulsed GTAW process [14]

Two types of pulsed-GTAW, high-frequency and low-frequency, are used. Low-frequency (1-10 Hz) modulation of current is used for reduced distortion, improved tolerance to dissimilar thicknesses and materials, improved bead contour, reduced residual stresses and reduced thermal buildup. High-frequency (kHz and MHz) pulsed-GTAW is used to improve arc stiffness, achieve high energy density, achieve high penetration and enable higher welding speeds. Distortion or warpage, especially on thin materials, is reduced by using pulsed GTAW. Another important application is laying the root run in pipe welding; this reduces heat buildup and consequently minimises variation in root penetration. Tube-to-tube-plate welds are particularly suitable for pulsed-GTAW as they involve dissimilar thicknesses and circumferential joints [8, 20].

1.3 Requirements of quality welding

Quality welding is essential across various industries because it has a direct impact on the structural integrity, performance, and safety of welded components and structures. Several key factors contribute to the need for quality welding. First and foremost, precise control over welding parameters such as heat input, welding speed, and shielding gas composition is crucial to ensuring proper fusion and minimising defects like porosity, cracks, or incomplete penetration. Furthermore, choosing the right welding techniques and equipment according to the materials and application requirements is crucial for producing high-quality welds. Proper preparation of welding surfaces, including cleaning, removing contaminants, and ensuring proper fit-up, is also critical to avoid weld contamination and ensure strong metallurgical bonds. Quality welding practices also involve post-weld inspections, non-destructive testing, and adherence to industry standards and codes to verify the integrity of welds and meet regulatory requirements. Ultimately, the emphasis on quality welding not only ensures the structural strength and durability of welded components but also contributes to overall operational reliability, cost-effectiveness, and safety in diverse engineering and manufacturing contexts [18].

1.4 Challenges in welding of titanium alloys

Most titanium alloys can be welded using fusion or solid-state welding processes. The weldability of titanium alloys is usually assessed on the basis of the toughness and ductility of the weld metal [8]. Commercially pure grades have relatively good weldability in comparison to other titanium alloys. Titanium alloys exhibit decreased weld metal ductility and toughness. Indeed, titanium alloy welds are substantially immune to many weld cracking problems. Despite these and other beneficial characteristics of titanium alloy welds, engineers and scientists believe that titanium and its alloys are difficult to weld due to their high reactivity to atmospheric gases at elevated temperatures. Other than the high reactivity of titanium, there are some other challenges in welding titanium alloys, including porosity, ferrite contamination, and grain growth in the HAZ and weld regions of titanium [18, 21].

1.4.1 Atmospheric contamination

Atmospheric contamination is very severe during the welding of titanium alloys because they absorb oxygen, nitrogen, and hydrogen even at a temperature as low as 427 °C. Excessive absorption of these gases, increases tensile strength but embrittles the weld and nearby region [3]. Thus, the ductility of the fusion weld depends on the effectiveness of gas shielding. Therefore, the welding area must be clean and protected using an inert atmosphere. A few complicated arrangements to protect the weldment using inert gases are commercially available, which are difficult to use and increase the cost of titanium welding. An affordable and simple design shielding set-up is always needed to reduce the cost of titanium welding [21, 22].

1.4.2 Porosity

Porosity is the most common problem, particularly when square buttweld joints are produced. Trapping of gas bubbles between dendrites during solidification causes this phenomenon. Gas bubbles are formed due to variations in the solubility of different gases at different temperatures, moisture in the welding area, or contamination in the filler and parent metal surfaces. Therefore, to avoid porosity in titanium welds, proper shielding and cleaning are crucial to eliminating porosity in the weld region [3, 21].

1.4.3 Ferrite contamination

Due to metallurgical incompatibility, when titanium reacts with any form of ferrite, it forms very hard and brittle intermetallic compounds and becomes susceptible to the formation of cracks. The embedding of iron particles into the surface of the material can be minimised by avoiding steel fabrication operations near titanium components, covering components to avoid airborne dust and ferrite particles settling on the surface, not using tools previously used for steel, scratch brushing the joint area before welding, and not handling the cleaned component with dirty gloves. Furthermore, iron-free filler metal can be utilized during welding [3].

1.4.4 Grain growth in weld and HAZ

In addition to the previously mentioned challenges, excessive grain growth in the weld region and heat-affected zone (HAZ) in titanium welds also pose significant challenges [23, 24]. Titanium alloys possess a very narrow solidification range and transformation kinetics, resulting in grain coarsening in the weld region. Grain coarsening in the HAZ of titanium alloys occurs due to the high temperatures experienced during welding, and subsequent cooling cycles lead to thermal gradients, promoting grain growth. As a result, optimal and controlled heat input is critical to preventing excessive grain growth in the weld region and the HAZ of titanium welds [3].

1.5 Requirement of dissimilar welding

The requirement for dissimilar welding arises from the need to join materials with different compositions, properties, or thicknesses to create complex structures or components with specific performance characteristics. Modern industries require innovative, high-performance, and cost-effective products and structures that take advantage of the strengths of different materials while addressing specific design and functional requirements. Dissimilar welding plays a crucial role in various industries, such as aerospace, automotive, energy, and manufacturing, where different materials may need to be combined to meet design requirements or address specific challenges [18, 25-28].

1.5.1 Welding of dissimilar titanium alloys

Titanium alloys are most commonly used in nuclear and aerospace applications, where different mechanical properties are often required in different components. Therefore, these components are made using different grades of titanium alloys. Sometimes, these components are welded to fulfil their functionality. Welding of dissimilar titanium alloys possesses unique challenges and requires careful consideration of material properties, welding techniques, and process parameters to achieve high-quality and reliable welds. One of the primary challenges stems from the varying compositions and properties of different titanium alloys, which can lead to differences in melting temperatures, thermal expansion rates, thermal conductivity and metallurgical compatibility during welding. To achieve successful welds with the desired mechanical properties and performance characteristics, a comprehensive understanding of material properties, specialized welding techniques, filler metal selection, meticulous pre-weld preparation, and thorough post-weld inspections is required for dissimilar titanium alloy welding.