Comparison of Corrosion properties of Laser & TIG welded Ti-5Al-2.5Sn Alloy

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This report is submitted as a FYP thesis in partial fulfillment of the requirement for the degree of

(BE in Materials Engineering)

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June, 2017

Certificate

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Dedication

We dedicate this thesis to SCME and our beloved parents.

Acknowledgement

Thanks to Almighty Allah for the courage and strength to complete this Final Year Project.

We would like to use this opportunity to thank and appreciate efforts of our project supervisor Dr. Adeel Umer and co-supervisor Lecturer Muhammad Shamir. Their professional guidance and appreciative attitude helped us to gain our objective. We are thankful to other faculty of SCME as well.

We would like to dedicate our project to our families and loved ones for their constant support and prayers.

Abstract

The electrochemical corrosion behavior of Laser and TIG welded Ti-5Al-2.5Sn alloy was studied in 3.5% NaCl solution using potentiodynamic polarization. Comparisons between corrosion resistance of laser and TIG welded samples were made on the basis of corrosion potential (E_{corr}) and current density (i_{corr}) values obtained from the polarization curves. XRD and micro-structural analysis was done to determine the phase changes produced by these welding techniques. Micro-hardness was also evaluated using a Vickers Hardness Tester. Based on the E_{corr} and i_{corr} values, it was found that laser welded samples showed a higher corrosion resistance as compared to the TIG welded samples. XRD and micro-structural analysis showed the formation of α′ martensitic structure without prior β grains in case of laser welded samples and needle like α′ martensitic structure with equiaxed prior β grains in case of TIG welded samples. The hardness values observed were higher in case of laser welded samples.

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Abbreviations

1. LBW Laser Beam Welding
2. TIG Tungsten Inert Gas
3. YAG Yttrium Aluminum Garnett
4. BM Base Metal
5. HAZ Heat Affected Zone
6. FZ Fusion Zone
7. XRD X-ray Diffraction
8. E_{corr} Corrosion Potential
9. i_{corr} Corrosion Current Density

Chapter 1: Introduction

Titanium alloys are widely being used in off shore applications, aerospace applications and biomedical applications. It is due to the fact that they have superior strength to weight ratio and they demonstrate better corrosion resistance in aqueous media and especially salt water solution and other hostile environments. Keeping in view the biomedical applications, titanium alloys are biocompatible and have better bio adhesion. Favorable mechanical properties, better process ability and availability on low price make titanium alloys suitable for a number of applications[1, 2].

1.1 Applications of titanium alloys

1.1.1 Offshore applications

In sea water and in aqueous media, titanium alloys have high corrosion resistance. Weight is also a general consideration for off shore applications. The strength to weight ratio is high which makes titanium alloys most suitable for marine and underwater applications. Use of titanium alloys in subsea applications, productions platforms and vessels will improve the life and reliability of such components. Crevice corrosion threshold temperature of titanium alloys is above 250° C. Extensive testing for offshore applications demonstrate excellent corrosion properties of titanium alloys.

Titanium maintains its passive behavior even in heavily polluted sea water. Localized corrosion does not occur in titanium and its alloys below 70℃. Pitting corrosion temperature is higher as compared to that of crevice corrosion. Also, titanium alloys show resistance to microbiologically influenced corrosion (MIC) [1].

1.1.2 Aerospace applications

Titanium alloys are being used extensively in aero engines and in space shuttles due to better strength to weight ratio. Functionality and reliability of titanium alloys for these applications makes them the most suitable for these critical aerospace applications. Titanium alloys provide significant weight reduction, stability at high temperature, better corrosion resistance, and high galvanic compatibility with polymer matrix composites. Not only has it provided the required mechanical properties for these applications, titanium alloys have good cast-ability, machine-ability, weld-ability and formability which have a great impact on reducing the cost of manufacturing [1].

1.1.3 Biomedical applications

Medical progress requires special properties for biomaterials. Tailor-made materials are required for particular applications. Biomaterials require corrosion resistance, biocompatibility, bio-adhesion, easy formability and better availability. Titanium and its alloys provide the required properties which makes it suitable for biomedical applications. It is corrosion resistant and maintains the passivity in the human body fluids [1].

1.2 Common titanium alloys and physical metallurgy

Allotropic transformation of pure titanium is observed from hcp (α) to bcc (β) when temperature is raised about 882℃. Alloying elements which are added to titanium can have three different effects. They can

i. Raise temperature of α-β transition and bring stability to α phase.
ii. Lower the temperature of α-β phase transition and bring stability to the β phase.
iii. May only act as a solid solution strengthener and does not affect the transition temperature.

Nitrogen, carbon and oxygen have α stabilizing affect and they raise the transition temperature. Similarly, hydrogen has β stabilizing effect and it lowers the transition temperature. Addition of interstitial elements raises the strength but decreases the ductility. It also increases the risk of embrittlement [3].

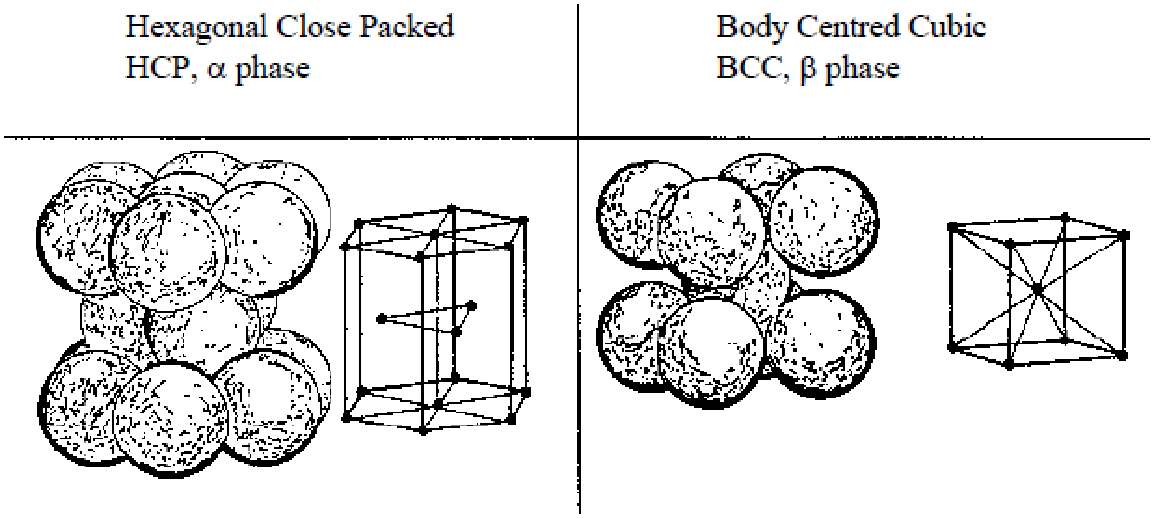


Fig. 1.1 Shows two main crystal structure of Titanium [2]

α+β region exist between the α phase and β phase. The width increases if concentration of solute increases.

Titanium alloys have three major groups, which are α alloys, α+β alloys and β alloys. The phase which dominates at room temperature is decided by the type and quantity of alloying element.

Alloying element	Range (wt%)	Effect on structure
Aluminium	2 to 7	Alpha stabilizer
Tin	2 to 6	Alpha stabilizer
Vanadium	2 to 20	Beta stabilizer
Molybdenum	2 to 20	Beta stabilizer
Chromium	2 to 12	Beta stabilizer
(Copper)	2 to 6	Beta stabilizer
Zirconium	2 to 8	Alpha and beta strengthening
Silicon	0.2 to 1	Improves creep resistance

Fig. 1.2 Shows alloying elements and their effect [3]

1.2.1 α alloys

Titanium alloys and pure titanium containing the α stabilizing elements are known as α alloys. Aluminum and tin are examples of α stabilizing elements. A stabilizing solute elevate the α+β/α transition temperature. Simple metals or non-transition metals are generally the α stabilizing solutes. Inter-metallic compounds having hexagonal structure are formed by the addition of simple metals [2].

1.2.2 α+β alloys

α+β system contain one or more α stabilizing element together with one or more β stabilizing element. At room temperature, a mixture of α and β phase exists, which depends upon the type and quantity of β stabilizing element [2, 3].

1.2.3 β alloys

BCC phase is stabilized by transition metal solutes. β alloys contain additions of vanadium, niobium, tantalum and molybdenum. Heating to slightly elevated temperature or performing cold working of β alloy at an ambient temperature can result in transformation to α phase. Meta-stable β alloys are generally aged at temperature of 450℃ to 650˚C so that the β phase is partially transformed to β phase. Finely dispersed particles of α are formed in the retained β which makes the strength level comparable to that of α+β alloys [3].

1.3 Processing and manufacturing of titanium alloys

Processing of titanium alloys involves four different steps.

i. Formation of sponge, which involves reduction of titanium ore to porous form of titanium.
ii. Melting of sponge or master alloys for the formation of ingot.
iii. Primary fabrication of ingots.
iv. Formation of finished shaped involving secondary fabrication.

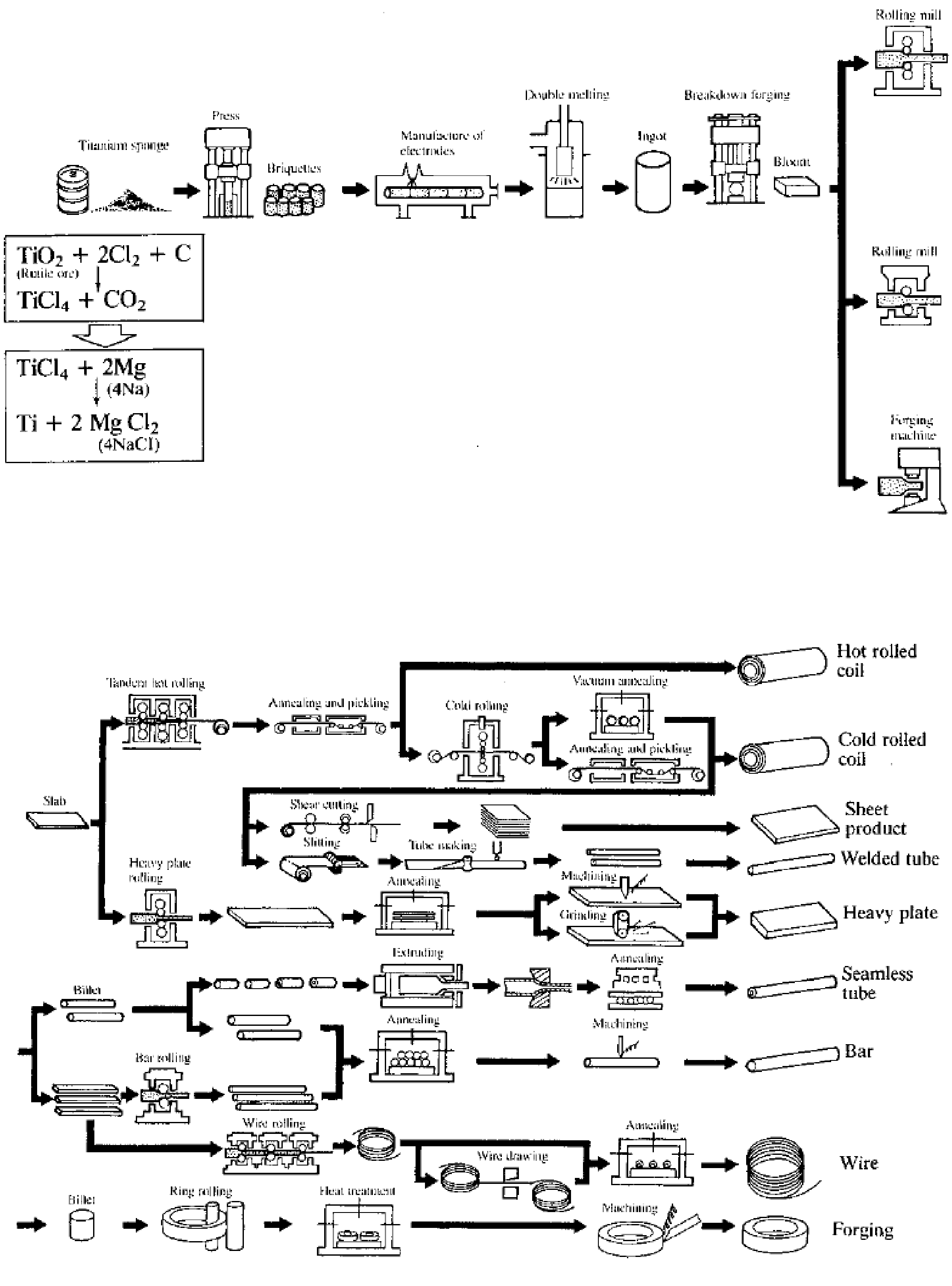


Fig. 1.3 Processing & Manufacturing of Titanium [3]

1.4 Mechanical properties

1.4.1 Properties (Mechanical) of α alloys

These alloys have satisfactory strength, good weld-ability and creep resistance together with high toughness. Ductile to brittle fracture behavior is absent in these alloys, which makes these alloys suitable choice for cryogenic applications [2].

1.4.2 Properties (Mechanical) of α+β alloys

Heat treatment affects the properties of α+β alloys. Microstructure and precipitation states of β components can be adjusted by heat treatments, which results in formation of components with different mechanical properties. These alloys demonstrate good fabric ability, moderate elevated temperature strength and high strength at room (moderate) temperature [2, 3].

1.4.3 Mechanical properties of β alloys

β alloys have excellent formability and good ductility. They have low basic strength but good toughness. β alloys are not suitable for elevated temperature service without over aging treatment. Aging of β alloys increases fracture toughness compared to that of α+β alloys [3].

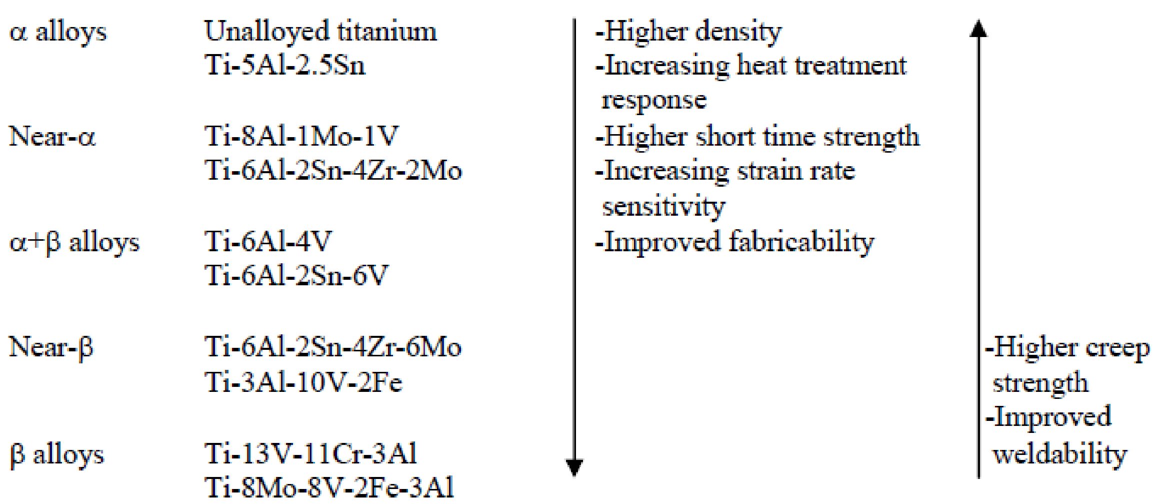


Fig 1.4Alloying effect on structure and properties of Titanium alloys[2]

			Impurity limits, wt%					Nominal composition, wt%				
Designation	YS (MPa)	TS (MPa)	N (max)	C (max)	H (max)	Fe (max)	O (max)	Al	Sn	Zr	Mo	Others
Unalloyed grades												
ASTM Gr.1	170	240	0.03	0.10	0.015	0.20	0.18	....	....	....	....	....
ASTM Gr.2	280	340	0.03	0.10	0.015	0.30	0.25	....	....	....	....	....
ASTM Gr.3	380	450	0.05	0.10	0.015	0.30	0.35	....	....	....	....	....
ASTM Gr.4	480	550	0.05	0.10	0.015	0.50	0.40	....	....	....	....	....
ASTM Gr.7	280	340	0.03	0.10	0.015	0.30	0.25	....	....	....	....	0.2 Pd
α and near-α alloys												
Ti-0.3Mo-0.8Ni	380	480	0.03	0.10	0.015	0.30	0.25	....	....	....	0.3	0.8 Ni
Ti-5Al-2.5Sn	760	790	0.05	0.08	0.02	0.50	0.20	5	2.5	....	....	....
Ti-5Al-2.5Sn-ELI	620	690	0.07	0.08	0.0125	0.25	0.12	5	2.5	....	....	....
Ti-8Al-1Mo-1V	830	900	0.05	0.08	0.015	0.30	0.12	8	....	....	1	1 V
Ti-6Al-2Sn-4Zr-2Mo	830	900	0.05	0.05	0.0125	0.25	0.15	6	2	4	2	
Ti-6Al-2Nb-1Ta-0.8Mo	690	790	0.02	0.03	0.0125	0.12	0.10	6	....	....	1	2 Nb, 1 Ta
Ti-2.25Al-11Sn-5Zr-1Mo	900	1000	0.04	0.04	0.008	0.12	0.17	2.25	11.0	5.0	1.0	0.2 Si
Ti-5Al-5Sn-2Zr-2Mo (a)	830	900	0.03	0.05	0.0125	0.15	0.13	5	5	2	2	0.25 Si
α+β alloys												
Ti-6Al-4V (b)	830	900	0.05	0.10	0.0125	0.30	0.20	6.0	....	....	....	4.0 V
Ti-6Al-4V-ELI (b)	760	830	0.05	0.08	0.0125	0.25	0.13	6.0	....	....	....	4.0 V
Ti-6Al-6V-2Sn (b)	970	1030	0.04	0.05	0.015	1.0	0.20	6.0	2.0	....	....	0.75 Cu, 6.0 V
Ti-8Mn (b)	760	860	0.05	0.08	0.015	0.50	0.20	....	....	....	....	8.0 Mn
Ti-7Al-4Mo (b)	970	1030	0.05	0.10	0.013	0.30	0.20	7.0	....	....	4.0	....
Ti-6Al-2Sn-4Zr-6Mo (c)	1100	1170	0.04	0.04	0.0125	0.15	0.15	6.0	2.0	4.0	6.0	....
Ti-5Al-2Sn-2Zr-4Mo-4Cr (a, c)	1055	1125	0.04	0.05	0.0125	0.30	0.13	5.0	2.0	2.0	4.0	4.0 Cr
Ti-6Al-2Sn-2Zr-2Mo-2Cr (a, b)	970	1030	0.03	0.05	0.0125	0.25	0.14	5.7	2.0	2.0	2.0	2.0 Cr, 0.25 Si
Ti-3Al-2,5V (d)	520	620	0.015	0.05	0.015	0.30	0.12	3.0	....	....	....	2.5 V
β alloys												
Ti-10V-2Fe-3Al (a, c)	1100	1170	0.05	0.05	0.015	2.5	0.16	3.0	....	....	....	10.0 V
Ti-13V-11Cr-3Al (c)	1100	1170	0.05	0.05	0.025	0.35	0.17	3.0	....	....	....	11.0 Cr, 13.0 V
Ti-8Mo-8V-2Fe-3Al (a, c)	1100	1170	0.05	0.05	0.015	2.5	0.17	3.0	....	....	8.0	8.0 V
Ti-3Al-8V-6Cr-4Mo-4Zr (a, c)	830	900	0.03	0.05	0.020	0.25	0.12	3.0	....	4.0	4.0	6.0 Cr, 8.0 V
Ti-11.5Mo-6Zr-4.5Sn (b)	620	690	0.05	0.10	0.020	0.35	0.18		4.5	6.0	11.5	....

Fig. 1.5 Summary of titanium alloys[3]

1.5 Ti-5Al-2.5Sn (Grade 6)

Ti-5Al-2.5Sn is a weld-able alloy with intermediate strength. It has moderate strength and excellent weld-ability. It is well suited for applications at cryogenic temperatures and demonstrates excellent combination of strength and toughness. Its density is 4.48g/cm3. It is available as sheet, plate, strip, bar, wire, forgings and extrusions. This alloy can be cast, welded and machined and has a very high fracture toughness at room temperature and elevated temperature.

Ti-5Al-2.5Sn is used to make castings and rings of gas turbines engines. Aerospace structural members in hot spots, rocket motor casing, aircraft forgings and extrusions, ordinance equipment, chemical processing equipment and other applications which require good fabricability and excellent weld-ability, better oxidation resistance and intermediate strength at service temperature use Grade 6 titanium alloy. It is also used in liquid hydrogen tanks and high pressure vessels at temperature below -195˚C.

Microstructure of Ti-5Al-2.5Sn is either acicular or equiaxed α**.** Acicular α is observed after thermal excursion above β transus temperature. Equiaxed α is formed when the metal is worked below the β transus temperature, followed by annealing in the α field. Very small amount of β exists in the microstructure of Grade 6 titanium alloy[4].

β transus: α phase is formed from β phase when cooled from 1090˚C to 1040˚C.

α transus: Heating α to β from 955˚C to 985℃.

Beta transus	1040 to 1090 °C	(1900 to 2000 °F)
Liquidus temperature	1590 ± 20 °C	(2895 ± 35 °F)
RT tensile modulus	110 to 125 GPa	(16 to 18 × 10^6 psi)
Density(a)	4.48 g/cm^3	(0.162 $lb/in.^3$)
Electrical resistivity(a)	1.6 μΩ · m	
Magnetic permeability	Nonmagnetic	
Specific heat capacity(a)	530 J/kg · K	(0.127 Btu/lb · °F)
Thermal conductivity(a)	7.8 W/m · K	(4.5 Btu/ft · h · °F)
Thermal coefficient of linear expansion(b)	9.4 x 10^{-6}/°C	(5.2 x 10^{-6}/°F)

Fig 1.6 Typical physical properties of Ti5Al2.5Sn[4]

1.5.1 Corrosion properties

Protective oxide film spontaneously forms and remains stable in mildly reducing to highly oxidizing environments. Small addition of commercially used alloying elements or trace alloying impurities has minor effect on corrosion resistance of alloy in passive environment. Corrosion of alloy is expected in warm, concentrated, low pH chloride salt. Acidic solutions which are reducing in nature and strong oxidizers may result in corrosion of the alloys. Ionize-able fluoride compounds and dry chlorine gas may activate the surface of alloy and result in corrosion [4].

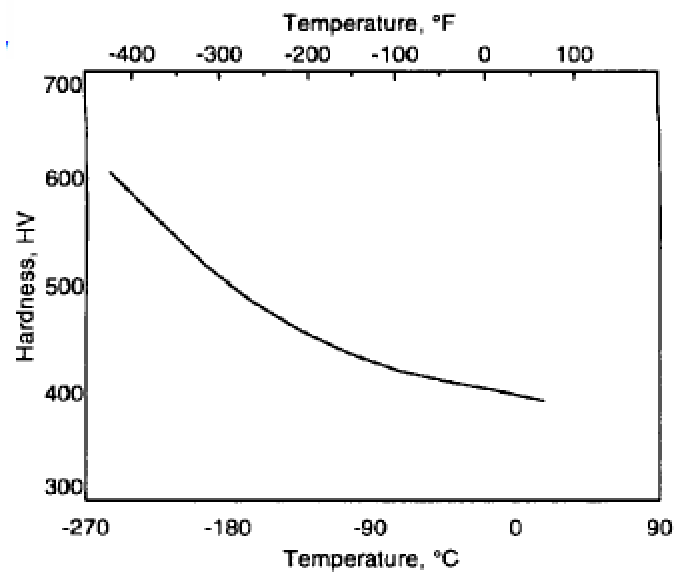


Fig. 1.7 Hardness of Ti5Al2.5Sn at low temperature[4]

Table 1.1 Typical hardness at room temperature [4]

Condition	Hardness		
	Brinell, HB	Rockwell C, HRC	Knoop, HK
Annealed, Std O_2	...	30-36 (typical) 28 (min)	...
Annealed, ELI O_2	...	30-36	...
Unwelded ELI sheet	...	33.2	265
Single-bead weld of ELI sheet	...	28	310
Annealed bar	290	30-31	...
As cast	321 typical 335 max	...	...

1.6 Joining

Ever since the history of mankind on earth, the joining of dissimilar or similar materials has a great importance for the manufacturing of different useful tools, products and different structures. Joining is considered as the oldest manufacturing technology. The history of joining process started when a split stick was first joined to a broken stone. This earliest production of practical instruments by amassing straightforward parts without a doubt more likely than not set off an entire rash of progressively more intricate, helpful, and efficient devices, and in addition a completely new way to deal with building covers from Nature's components and from adversaries[5]. It additionally should have immediately progressed or declined into inventive methods for delivering efficient protective and hostile weapons for war: longbows and longboats, crossbows and strongholds, swords and attack machines. With the progression of time, the requirement for and benefits of joining have not decreased; they have developed. More differing materials were created into more complex segments, and these parts were participated in more assorted and viable approaches to deliver more advanced congregations.

1.7 Welding

Welding, according to most of the people, is considered a new process. Different types of welding like arc welding which consists of white-blue electric arcs, robots having spark spitting resistance for automobile welding, and welding having very thin heat effected zones like electron beam welding and laser welding shows that how much the technology has improved over the years in the field of joining[6]. Although the above mentioned welding processes are quite new, yet the welding technique is very old. Welding techniques like forge or hammer welding is very old. The basic purpose of welding is the fabrication of metals like copper, tin, iron, titanium etc. With the help of welding, small pieces can be joined to make large objects. The main principle of welding is that it involves the bringing of materials, which are to be joined so close that atoms seek to create a stable electronic configuration between them. In its broadest sense, welding incorporates any procedure that makes materials join through the appealing activity of inter atomic or intermolecular strengths, rather than absolutely naturally visible or even minute mechanical interlocking forces[7]. Welding is fundamentally imperative in present day fabricating from a mechanical and additionally a financial point of view. It has been evaluated that the greater part of the gross national result of all industrialized nations comes to fruition straightforwardly or in a roundabout way from welding. Welding is utilized to join materials into parts and parts into gatherings and structures.

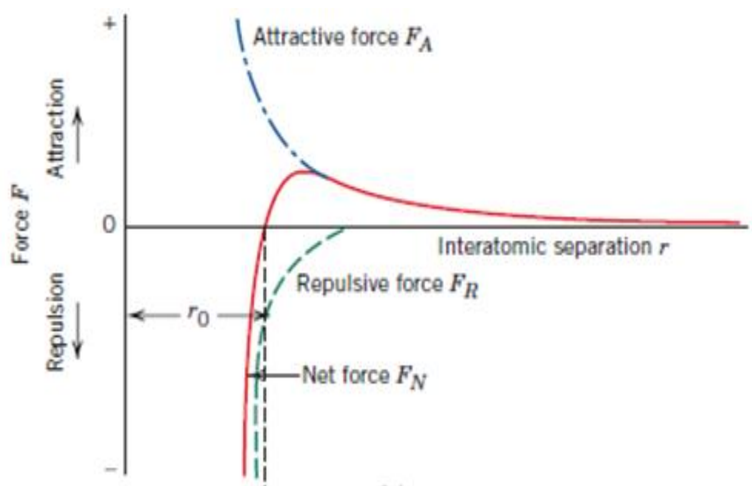


Fig. 1.8 Effect of inter-atomic separation [7]

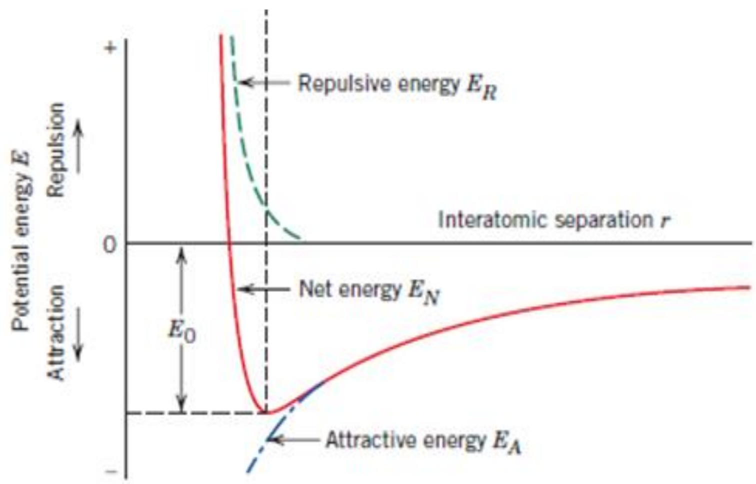


Fig. 1.9 Effect of inter-atomic separation on Potential Energy [7]

Inter diffusion at atomic levels is the key to all welding between the materials being joined, regardless of whether that diffusion happens in the solid, liquid, or mixed state. Nothing adds to joining superior to real trade of ions, atoms, or molecules.

When two or more atoms come close to each other from a separation, which is infinite, a force between them arises which is known as electrostatic force. As the distance between the atoms is decreased, the electrostatic force goes on increasing [7]. But at the same time an opposite force, which is called repulsive force also arises due to the sensing of the negative electronic cloud between the atoms. Due to these attractive and repulsive forces, a point will come when both repulsive and attractive forces balance each other and bonding takes place. At this point, minimum value of the energy exists and the surface is energetically stable. In the binding region, when all the atoms are at equilibrium spacing, stable electronic configuration by the atoms is achieved by transferring or by the sharing of electrons. The phenomenon explained above is same for oppositely charged ions like neutral atoms. This phenomenon leads to the formation of ceramics. This process leads to the formation of polymers if the molecules consist of permanent or induced dipoles. This tendency of bonding of the atoms is considered as the basic fundamentals of welding, which includes electromagnetically based physical forces for joining. The biggest challenge in the welding process is bringing the atoms in to their equilibrium spacing. If the particular equilibrium spacing is achieved, both perfectly flat surfaces are welded together. For this situation, there is no remainder of the earlier physical interface and there is no interruption of the nuclear level structure of either material required in the joint. In reality, the surfaces of both materials are not quite smooth due to which perfect matching doesn't takes place and a perfect weld cannot be created just by bringing both materials close together. Surfaces of the materials have high irregularity. There exist only few points on which equilibrium spacing or intimate contact can be achieved.

1.8 Welding of Titanium

As titanium is being used in some critical applications including bio materials, marine, aerospace, chemical and petrochemical so the welding of titanium is of prime importance. Some of the titanium alloys are easily weld able while some alloys are difficult to weld. Different welding techniques are being used for the welding of titanium alloys depending upon the properties of the alloy and the application in which it is being used [8]. An important consideration is that maintainability, reliability and safety are considered carefully while selecting any welding technique. Normally, titanium and its alloys are welded by the techniques which are used for the welding of Aluminum and Austenitic stainless steel. Titanium is highly reactive and it can react with the environment if the temperature exceeds above 550 degrees Celsius [8]. Therefore, some important precautions like shielding from the environment are used while welding titanium and titanium alloys.In our project, we used two types of welding for the comparison of corrosion properties of near α titanium alloy. These two types of welding are laser welding and tungsten inert gas welding.

1.9 Laser Welding

LASER is an abbreviation of "Light amplification by stimulated emission of radiation." The main elements of which a laser consists are:

- Medium (for laser emission)
- Pump (Input energy)
- Total Reflecting mirror (Rear)
- Partial reflecting mirror(Front)
- Resonator

1.9.1 How laser beams are generated

There are three main steps in the laser generation process:

1. Energy is provided to the medium by the pump. Due to this energy, electrons in the medium are excited and are temporarily elevated to a higher energy state. But electrons always move towards the lower energy in order to balance themselves. When electrons move from higher energy to lower energy state, they lose extra energy in the form of a photon. This process is known as spontaneous emission[9].
2. The photons, which are emitted in the above process strike to the other electrons which are at higher energy state and due to this a large number of photons, are generated. The photons are considered to be in phase i-e they have the same wavelength and same direction. This process is called stimulated emission.
3. The emitted photons don't have any specific direction and are they are emitted in all directions. Some of the electrons strike the resonator mirrors after travelling through the laser medium. The function of these mirrors is that direction of amplification for stimulated emission is defined. Amplification occurs when the number of electrons is greater in excited state as compared to lower energy level [9].

1.9.2 Types of laser welding

Laser welding is divided into the following types

1. Gas lasers
2. Solid state lasers

1.9.2.1 Gas Lasers

In gas lasers, mixture of different gases is used which include nitrogen and helium. CO_2 lasers are also being used. The mechanism of CO_2 laser welding is that it uses a small current but voltage power is very high which helps in exciting the gas mixture with the help of laser medium. In CO_2 lasers, nitrogen or helium is used as a medium in the high purity CO_2[10].

1.9.2.2 Solid State Lasers

Solid state lasers include Nd:YAG and ruby laser. Nd:YAG is a crystal, synthesized from Yttrium Aluminum Garnett. Host material in this case is Yttrium Aluminum Garnett and having a small concentration of neodymium, which acts as an active element. Concentration of doping of the neodymium in YAG is about 1-1.5%. This doping is done because it optimizes the lasing effect and excessive strains are prevented on the crystal. The size of Nd^{3+} ions is larger than Y^{3+} ions. This crystal is hard physically, isotropic in its optical properties and stable[10]. Another important property of neodymium is that it has high thermal conductivity due to which operation is possible at high level of powers as compared to any other doping element.

The type of laser welding which we used in our project is Nd:YAG pulsed laser welding.

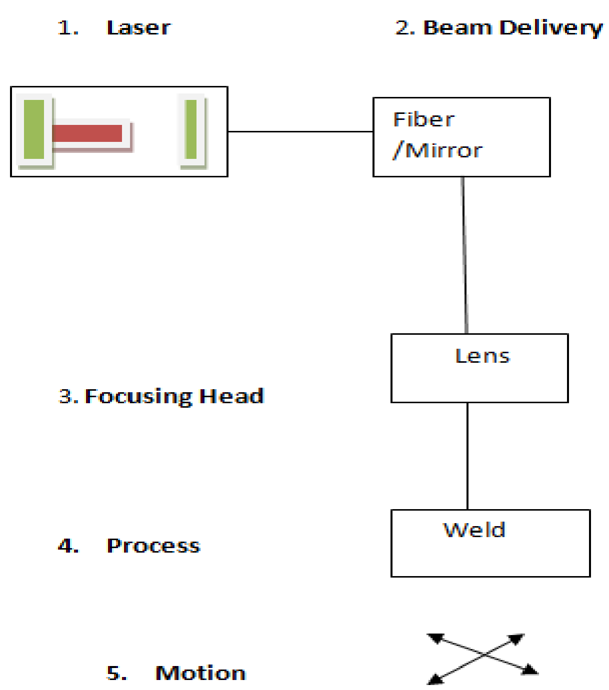


Fig. 1.10 Mechanism of LBW [9]

1.9.3 Pulsed Welding lasers

Nd:YAG laser which is pumped by a flash lamp is used for laser welding and the output of this laser is pulsed. The most robust and efficient material is Nd:YAG crystal in terms of generation of high heat generation and power inside a crystal rod. Flash lamp is required by the pulsed laser as compared to lasers that use Q-switching and diode pumping. This is because pulsing cannot be done with diodes and sufficient energy for welding cannot be provided with Q-switching [9].

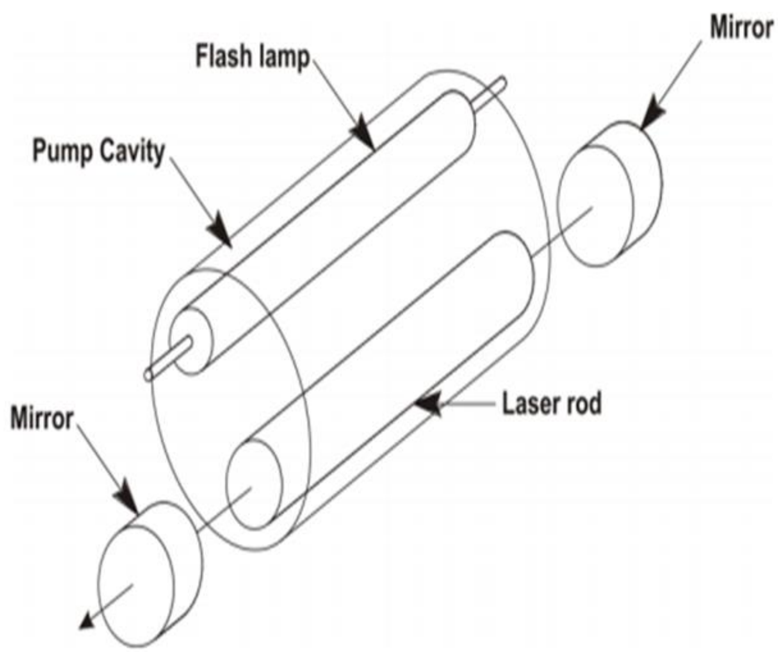


Fig. 1.11 Components of Pulsed laser welding [10]

1.9.4 Modes in laser welding

Following are the different modes used in the laser welding:

1. Conduction mode
2. Penetration/conduction mode
3. Keyhole mode

1.9.4.1 Conduction Mode

In this mode of laser welding, wide and shallow welds are obtained as it is performed at the energy density which is low

1.9.4.2 Penetration/conduction Mode

In this mode, medium level of penetration is achieved because penetration /conduction mode welding is performed at medium energy levels.

1.9.4.3 Keyhole Mode

In this mode, narrow and deep welds are produced. A vaporized materials filament is formed by the laser light which we call as keyhole. Way to the laser light is provided as it because of the keyhole, which is extended into the material. As the energy in this mode is delivered directly, therefore in order to achieve penetration, the material is not dependent on conduction. Due to this, the heat is minimized into the material and the heat affected zone is reduced.

1.9.5 Parameters of Laser welding

Following are the different parameters used in laser welding:

1.9.5.1 Peak Power

This parameter is directly selected on laser. Maximum power of the pulse is controlled by this parameter. Its unit is watt.

1.9.5.2 Width of pulse

The laser pulse duration is called pulse width. The unit of pulse width is milli seconds.

1.9.5.3 Repetition rate of pulse

Repetition rate of pulse is the total number of pulses of the flash lamp in one second. The units of the pulse repetition rate are pps or hertz.

1.9.5.4 Pulse Energy

The total energy, which is contained in a pulse is called pulse energy and it can be calculated by the product of width of pulse and peak power.

1.9.6 Shielding Gas

In the weld zone, the rapid oxidation due to the oxygen present in the atmosphere is prevented with the help of shielding gas. Inert gases like helium, argon or nitrogen are used for shielding. The strength of the weld and the mechanical properties cannot be affected by the use of shielding gas. Aesthetics of welds are also improved by the use of shielding gas. Heat affected zone is also minimized by the use of shielding gas.

1.10 Tungsten inert Gas (TIG) welding

It is basically an arc welding process. Heat is produced with the help of a non-consumable tungsten electrode. Inert gases like helium or argon are used for shielding purposes.

1.10.1 Principle

The basic principle of tungsten inert gas welding is that an electric arc between tungsten electrode and work piece produces fusion energy. As the welding is being carried out, shielding gas is used for the protection of weld pool and the arc in order to avoid the damaging effects caused by the atmospheric oxygen. Shielding gas reaches the weld zone with the help of a nozzle and atmospheric air is replaced by the shielding gas. It is different from the other arc welding processes in a sense that in other processes, electrode is consumed, while in tungsten inert gas welding, electrode is not consumed [11].

1.10.2 Basic components of TIG welding

Following are the basic components of the tungsten inert gas welding:

1.10.2.1 Welding Torch

The basic purpose of the welding torch is that it carries shielding gas and the current to the weld zone. It consists of a torch head and a welding handle which is electrically insulated. A switch is fitted on a torch handle which is used to turn on and off the shielding gas and the welding current.

1.10.2.2 Non-consumable tungsten electrode

For tungsten inert gas welding, the electrode which is used is made of tungsten. Tungsten in its pure form is very heat resistant and the temperature at which it fuses is 3380^0C. Electrode conductivity is increased by the addition of the small amount of different oxides of metals which helps in resisting higher loads of current. Due to the alloying of electrodes, they have longer life and ignition properties are also enhanced. The oxides of metals which are generally used for tungsten alloying are zirconium oxide, lanthanum oxide, thorium oxide and cerium oxide[11].

1.10.2.3 Shielding Gas

There are several functions of shielding gas. The most important function of the shielding gas is that it prevents atmospheric oxygen to enter the weld zone. Another important purpose of shielding gas is that it rates of heat and current transfer is enhanced. The two gases which are mainly used as shielding gases in tungsten inert gas welding are helium and argon. The criterion of choosing the shielding gas is the material which is to be weld.

1.10.3 Advantages of TIG welding

Following are the advantages of tungsten inert gas welding:

1. Welds with superior quality are produced which are generally defect free.
2. Spattering does not occur in this process.
3. One of the main advantages of this process is that it can be used with or without using filler material which depends on the application.
4. Weld penetration in tungsten inert gas welding is excellent.
5. Almost all the metals can be welded using this process.

1.10.4 Disadvantages of TIG welding

1. Deposition rate in this process because of non-consumable electrode. Consumable electrodes have higher deposition rate.
2. For thicker sections, it is less economical as compared to electrodes which are consumable.

1.10.5 Application areas

Tungsten inert gas welding is used in the jobs where high quality welds are needed. For example: combined power and heat plants, offshore jobs, food industry, petrochemical industry, nuclear industry and chemical industry.

Chapter 2: Literature Review

Table: 2.1 Shows the type of research done on different type of titanium alloys used in a wide range of applications.

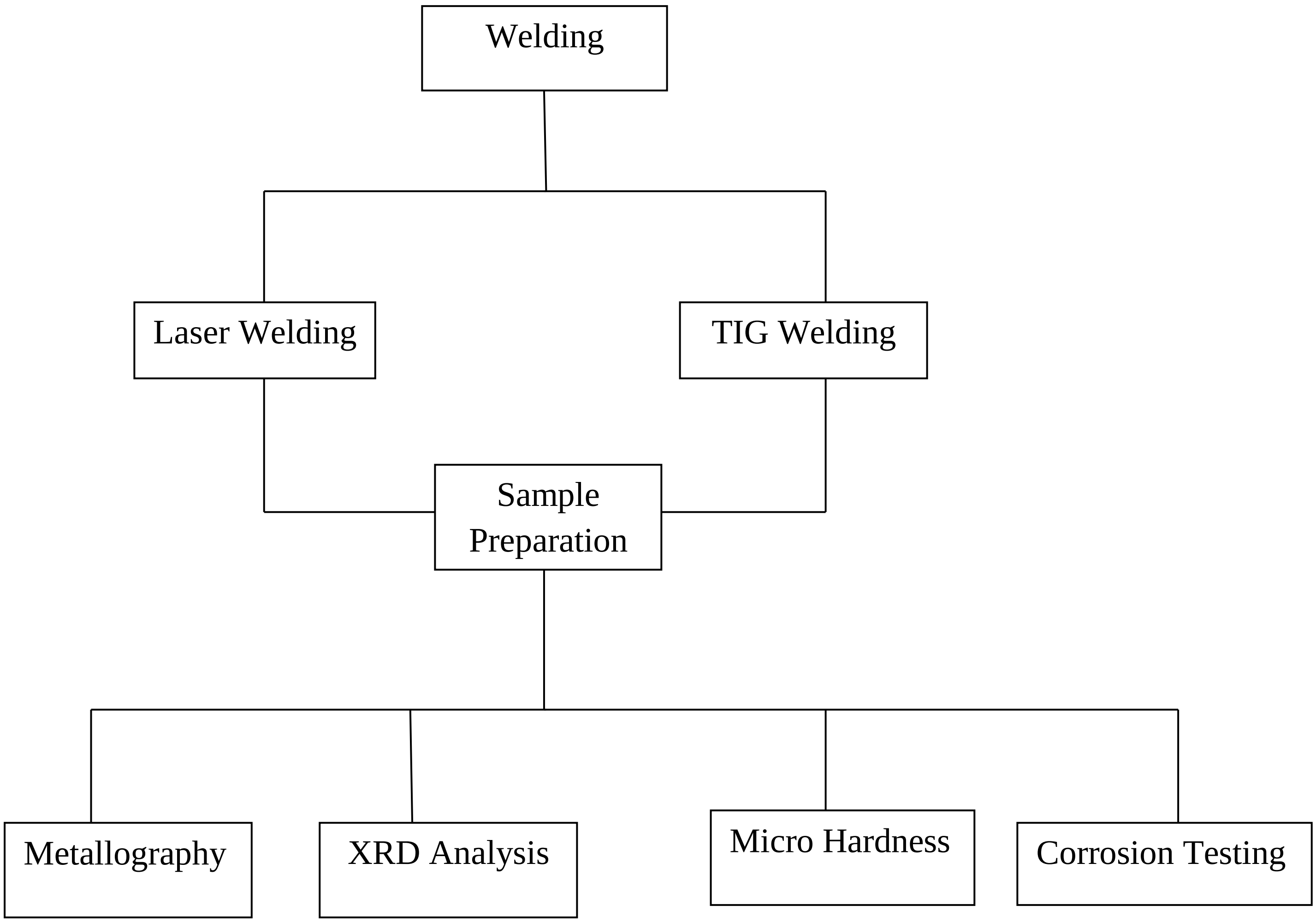
No.	Research Paper Title	Authors	Applications	Alloy
1.	Some studies on mechanical properties and microstructural characterization of automated TIG welding of thin commercially pure titanium sheets [12].	A. Karpagaraj, N. Sivashanmugam, K.Sankaranarayanasamy	Fabrication of airframe, aircraft engine parts, marine, orthopedic and dental implants, chemical parts and condenser tubing	C.P titanium
2.	Corrosion and galvanic coupling of heat treated Ti-6Al-4V alloy weldment [13].	M. Heidarbeigy, F.Karimzadeh, A. Saatchi	Implants such as pacemakers, defibrillators, catheters, cochlear, insulin pumps, stents, and orthopedic implants	Ti-6Al-4V
3.	Microstructure, micro-hardness and corrosion resistance of re-melted TiG2 and Ti-6Al-4V by a high power diode laser [14].	M.R. Amaya-Vazquez, J.M. Sánchez-Amaya, Z. Boukha, F.J. Botana	Widely employed in different fields (medical, aerospace, automotive, petrochemical, nuclear, power generation, etc.)	Ti Grade 2, Ti-6Al-4V
4.	Electrochemical characterization of Ti alloy in Ringer's solution for implant application [15].	Satendra Kumar, T.S.N. Sankara Narayanan	Bio-medical applications due to their low density, excellent biocompatibility, corrosion resistance.	Commercially pure Titanium, Ti–15Mo, Ti-6Al-4V

5.	Effects of CryoTreatment on Corrosion Behavior and Mechanical Properties of Laser-Welded Commercial Pure Titanium [16]	Yanping Zhu, Changyi Li, Lianyun Zhang	Used in dental devices owing to their low density, excellent corrosion resistance, and unique biocompatibility	Commercial Pure Titanium
6.	Microstructure and tensile properties of laser beam welded Ti–22Al–27Nb alloys [17]	Zhenglong Lei, Zhijun Dong, Yanbin Chen, Jian Zhang, Ruican Zhu	Aircraft engine applications due to their higher specific strength, fracture toughness and better room-temperature ductility	Ti-22Al-27Nb
7.	Investigation on the corrosion behavior of Ti–6Al–4V implant alloy by electrochemical techniques [18]	Robert Wen-Wei Hsu, Chun-Chen Yang,Ching-An Huang, Yi-Sui Chen	Used on the tibia component for total knee arthroplasty (TKA) prosthesis	Ti-6Al-4V
8.	A comparative study of pulsed laser and pulsed TIG welding of Ti-5Al-2.5Sn titanium alloy sheet [19]	M. Junaid, M.N. Baig, M. Shamir, F.N. Khan, K. Rehman, J. Haider	Used in Aerospace and marine applications	Ti-5Al-2.5Sn

Titanium alloys mostly Ti-6Al-4V are used in a wide range of applications including bio-medical, aerospace and dental applications. Most of the research done on titanium is related to Ti-6Al-4V alloy. As there has been no research regarding the corrosion behavior of welded Ti-5Al-2.5Sn alloy, so that is the purpose of our research to determine the corrosion properties of welded Ti-5Al-2.5Sn alloy. The most extensive work on this titanium alloy has been done by Junaid et al [19] in which they studied the effect of pulsed laser and TIG welding on the microstructure, micro-hardness, tensile properties, surface and sub-surface residual stress distribution and deformation and distortion of both the weldments. They determined that the less residual stresses, deformation and distortion and superior mechanical properties of pulsed laser welding made the process more feasible than TIG welding for Ti-5Al-2.5Sn alloy. We have continued the work further and studied the effect of laser and TIG welding on the corrosion properties of Ti-5Al-2.5Sn alloy in 3.5 % NaCl solution.

Chapter 3: Experimental Methodology

Table: 3.1 Shows the experimental procedure that was followed.



3.1 Welding

The parameters which are used for laser and TIG welding are given below:

3.1.1 Laser Welding parameters

Table 3.2 Shows the parameters for Laser welding

Current (A)	Frequency (Pulses/sec)	Speed (mm/min)	Stand of Distance (mm)
260	8	160	4

3.1.2 TIG Welding Parameters

Table 3.3 Shows the parameters for TIG welding

Primary Current (A)	Background Current (A)	Volts (V)	Welding speed (mm/min)
32	16	10	32.5

3.2 X-Ray Diffraction

3.2.1 Introduction of X-rays

X-ray diffraction or XRD is used for the identification of phases in a sample. Materials are identified with the help of XRD due to their unique structure which is crystalline [20]. X-ray diffraction has many applications which are as follow:

1. Detection of minority crystalline phases
2. Size of crystallite can be determined for polycrystalline materials and films.
3. Material percentage of amorphous and crystalline form.
4. Behavior of phase and texture of thin films of 50 angstroms.
5. Composition and strain in thin films can be determined
6. Residual stresses in ceramics and bulk materials can also be determined.

3.2.2 Sample preparation

The diffractometer was basically designed for the examination of samples in powder state. But it is being used in the examination of samples which have aggregates of crystalline nature instead of powder samples.

In our project, cutting of the samples of fusion zone, base metal and heat affected zone was done separately with the help of electro discharge machining(EDM) and each sample was placed in the XRD machine separately for the analysis of phase detection.

3.2.3 Parameters

Table 3.4 Shows the parameters used for XRD analysis

Radiations	1.54Å Cu
Scan mode	Reflection
Generator	20 KV, 5mA
Detector	Scintillation counter
2θ Range	20-80°
Step size	0.020
Scan Rate	0.5 sec/step

3.3 Metallography

Metallography was done to find the difference in the microstructure of heat affected, fusion zone and base metal and then comparing the microstructure of these three zones in both types of welding i-e laser welding and tungsten inert gas welding. The main steps in the metallography are as following:

3.3.1 Sample preparation

Both laser and TIG welding were done on 0.5mm thick Ti-5Al-2.5Sn plates. Sample preparation was carried out in the following manner.

3.3.1.1 Sample cutting

Sample cutting was done with the help of EDM (Electro discharge machining). Cutting of all the three zones of laser and TIG welded plates was done separately.

3.3.1.2 Cold Mounting

After cutting of samples, samples were placed in separate molds and cold mounting was done in polymeric resin and hardening agent was also used. After drying, samples were separated from molds.

3.3.1.3 Grinding

Grinding was done with different emery papers on grinding machine. The emery papers used in this process ranges from 120 to 1200. After grinding from each emery paper, sample was washed in order to remove contaminants. In order to remove scratches, sample was rotated at 90 degrees after each emery paper.

3.3.1.4 Polishing

After grinding, polishing of each sample was done on (GDI GRIPO 2V) polisher. First the samples were polished with 0.1 µm alumina powder, washed and then polished with

0.5 µm alumina powder. After polishing, samples were washed in distilled water and dried with the help of a drier.

3.3.1.5 Etching

Etching is a very important step in metallography process. After drying of sample, etching was done. Etching is done in order to see the grain boundaries, grain size and different phases present in the material. The etchant used for the etching of our samples has the composition of 2% HF, 6%HNO_3 and 92% distilled water. Etching time was 80 to 90 seconds. After etching, samples were again washed and dried.

3.3.1.6 Microscopy

All the samples were examined under the microscope (Optika 600) and images of the microstructures were taken at 500x magnification.

3.4 Micro Hardness testing

Fig. 3.1 Vickers Hardness Tester[7]

Micro hardness testing was done to determine the hardness values of BM, HAZ and FZ of laser beam welded and tungsten inert gas welded Ti-5Al-2.5Sn samples and comparing the difference in hardness of all the three zones of both welding. Vickers Hardness Tester was used for this purpose. The experimental procedure of micro hardness testing is as follows:

1) First of all, sample was placed on the digital micro hardness tester.
2) 500g load was used and dwell time was 10 seconds.
3) Lamp brightness was increased in order to see the microstructure clearly.
4) Sample was focused with the help of a focusing knob until the microstructure was clearly visible.
5) After this, we placed the indenter on the sample and pressed the start button.
6) The load was applied and indent was made on the sample.

7) After indentation, we changed the indenter to the lens and digital measurements of indent were taken on both axis.
8) After this, hardness value was calculated.

This process was performed on all the three zones including fusion zone, base and heat affected zone on both types of welding and then compared with each other.

3.5 Electrochemical testing

Electrochemical corrosion tests were performed on the samples obtained from the BM, FZ & HAZ for laser and TIG welded samples to determine the corrosion behavior of these different regions and compare them. The procedure is as follows:

3.5.1 Sample Preparation

Samples were prepared from laser and TIG welded 0.5mm thick Ti-5Al-2.5Sn plates. The procedure of sample preparation is as follows:

3.5.1.1 Sample cutting

Sample cutting was done with the help of EDM (Electro discharge machining). Cutting of all the three zones of laser and TIG welded plates was done separately.

3.5.1.2 Soldering

Samples from all the three zones were soldered using a Pb-Sn solder wire. Temperature was maintained at 265-270°C. It was done to attach a copper wire to the back of the samples to provide an electrical connection for corrosion testing.

3.5.1.3 Cold Mounting

Soldered samples were then placed in separate molds and cold mounting was done in polymeric resin and hardening agent was also used. After drying, samples were separated from molds.

3.5.1.4 Grinding

Mounted samples were then grinded using different emery papers on grinding machine. The emery papers used in this process ranges from 120 to 1200. After grinding samples were washed with distilled water. Grinding was done to remove any layer formed on the samples prior to performing corrosion tests.

3.5.2 Solution Preparation

The electrolyte used in the corrosion testing was 3.5% NaCl solution. The solution was prepared by mixing 3.5 grams of NaCl in 100 ml of deionized water. Fresh solution was prepared for each test. Lab grade NaCl of Merck was used.

3.5.3 Apparatus Used

A potentiostat model Series G-750 connected to a computer and Gamry Framework software was used to determine the corrosion potentials of the prepared samples from the three regions (BM, HAZ, FZ) of both laser and TIG welded specimens. A three electrode cell arrangement was used to conduct the corrosion tests. Graphite was used as counter electrode and saturated calomel electrode (SCE) was used as the reference electrode. Prepared samples served as the working electrodes. All the experiments were performed at the room temperature.

3.5.4 Potentiodynamic Polarization

Potentiodynamic polarization technique was applied to determine the corrosion potential (E_{corr}) and current density (i_{corr}) of the samples. The polarization curves were obtained in the scan range of -0.6 – 2V. The scan rate was maintained at 1mV/s. The test was repeated three times for each specimen. The equivalent weight was calculated to be 11.94 for Ti-5Al-2.5Sn alloy according to the ASTM G 102-89 standard. The exposed area of the samples is given in the Table 3.5.

Table 3.5 Shows the exposed area of samples

No.	Sample Name	Exposed Area cm^2
1.	Base Metal	0.19397
2.	HAZ LBW	0.255
3.	FZ LBW	0.3312
4.	HAZ TIG	0.183
5.	FZ TIG	0.1817

Chapter 4: Results and Discussion

4.1 X-ray Diffraction Results

XRD analysis was performed on the samples obtained from following three regions: BM (base metal), HAZ (heat affected zone), FZ (fusion zone) for both laser and TIG welded techniques for phase determination. In the figures 4.1 &4.2 below the XRD patterns obtained from these samples have been compared.

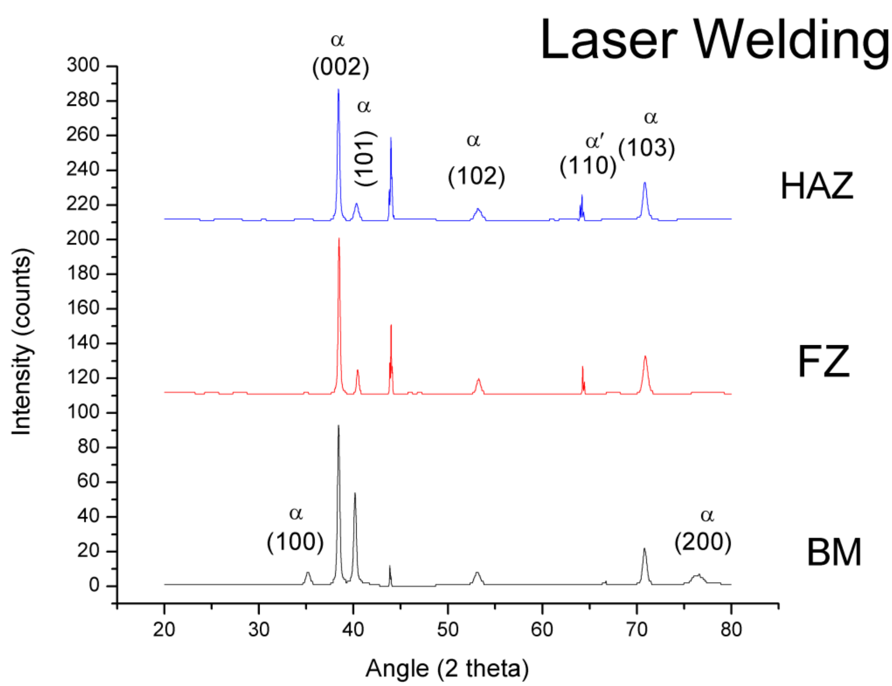


Fig. 4.1 XRD patterns of Laser welded samples

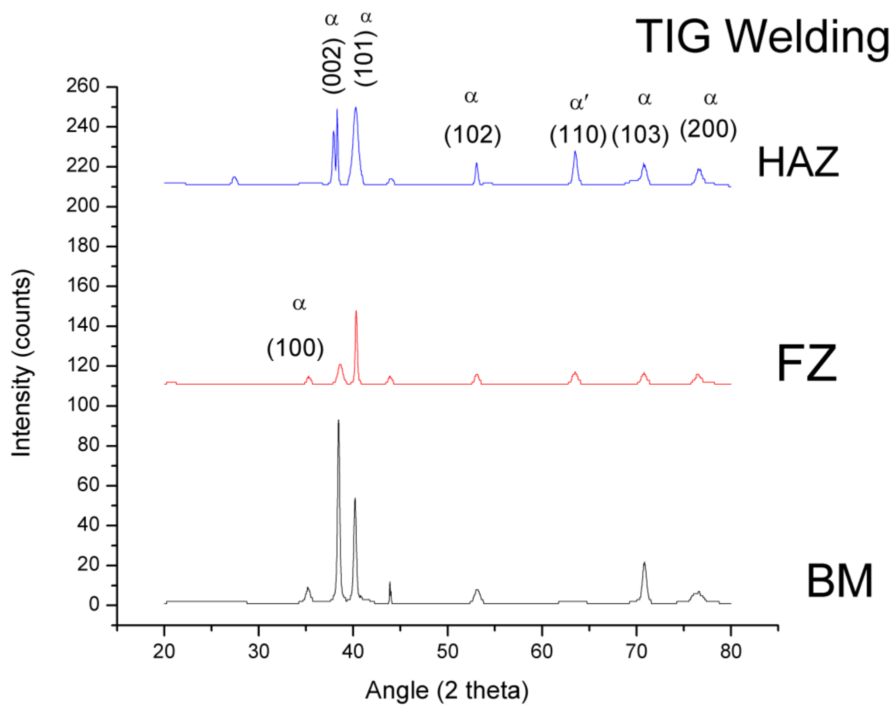


Fig. 4.2 XRD patterns of TIG welded samples

It is evident from the above figures that all the peaks are observed in the 2θ range of 30-80°. Most of the observed peaks are the characteristic of the titanium alloys showing α (hcp) phase and have been reported in the literature for different titanium alloys by Amaya-Vazquez et al[14], A. Karpagaraj et al[12]and others. Above figures show that observed peaks from laser and TIG welded samples occur at same angles with slight difference in intensity. With the exception of one peak at approximately 63°, all the observed peaks are same for the BM, HAZ and FZ for laser and TIG welded samples. In the XRD patterns of HAZ and FZ of laser welded samples the intensity of the peaks obtained at 40° is reduced as compared to base metal and a new peaks are observed at 43° which could not be identified from the literature or the X'pert High Score software. The peaks observed at 63° in FZ and HAZ of both laser and TIG welded samples show the presence of α′ martensitic structure. As both α & α′ peaks occur at same angle, so it can be assumed by the non-presence of the α peak at 63° in the base metal and later occurring in HAZ & FZ for both welding types samples that it corresponds to α′ phase.

It can be concluded from the XRD results that both the welding techniques produce a phase change which can lead to the difference in properties of for BM, HAZ and FZ regions.

4.2 Microstructure Analysis

Microsturcutre of the base metal is shown in figure 4.3. From the figure 4.3 it is evident that the microstructure of the base metal consists of equiaxed α grains in the prior β matrix. The difference in the mircosturcutres in BM, FZ and HAZ for both welding techniques results from the high temperatures experienced by these zones.

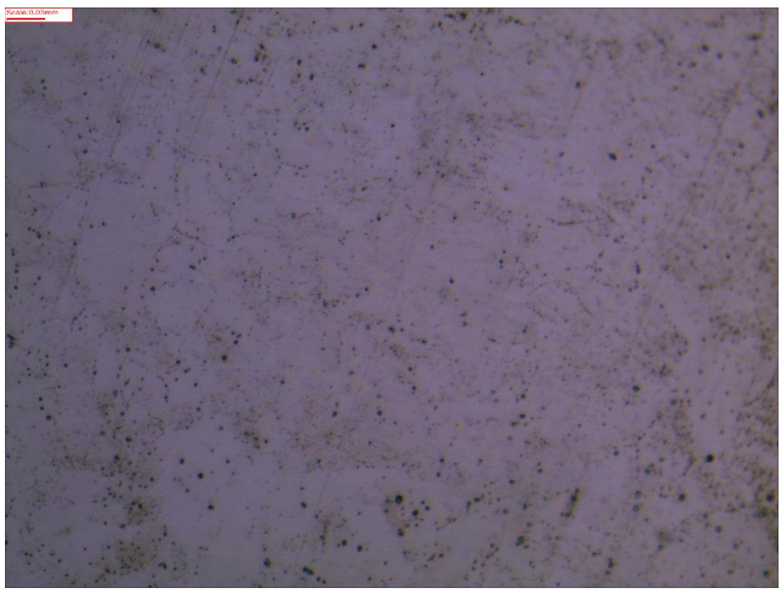


Fig. 4.3 Base Metal Microstructure at 500X

Microstructures of FZ & HAZ for laser welded samples are shown in the figures 4.4 (a) & (b) respectively. It is evident from fig. 4.4 (a) that FZ of laser welded sample has α′ martensitic structure without any prior β grains. This occurs because of the higher cooling rate and lower heat input as compared to TIG welding technique. This type of microstructure was also reported by Gao et al[11], Sun et al [21]and Zhang et al[22] for titanium alloys. The microstructure of HAZ as shown in figure 4.4 (b) is quite similar to the base metal with some elongation of the grains. This happens because the heat affected zone is very small in case of LBW.

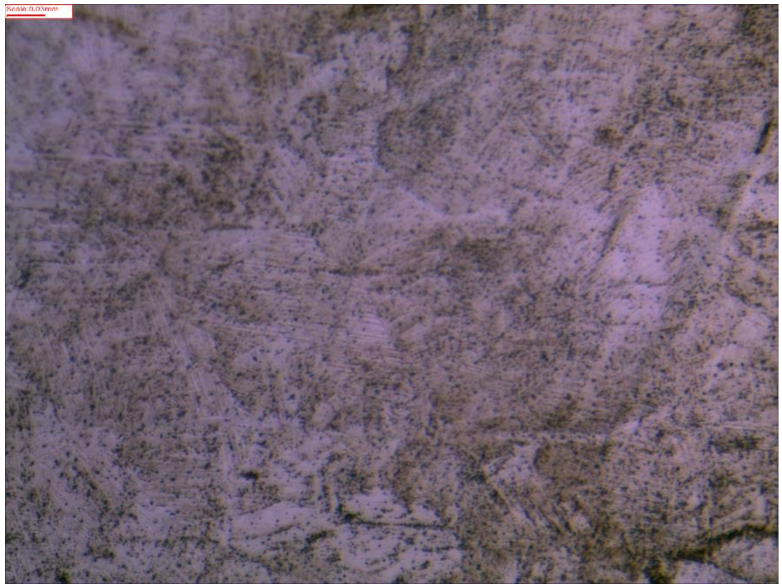


Fig 4.4 (a)

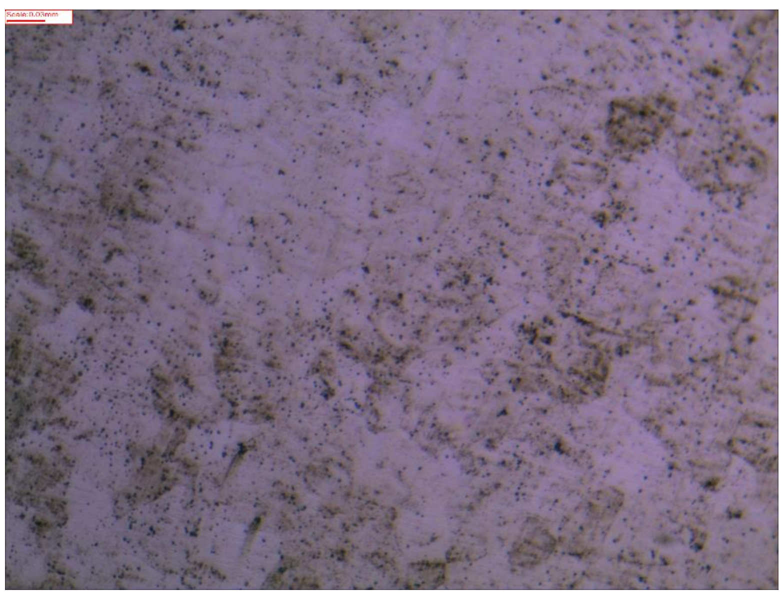


Fig 4.4 (b)

Fig.4.4 Microstructure of Laser welded (a) FZ (b) HAZ

Figure 4.5 (a) & (b) show the microstructures of TIG welded FZ and HAZ. It can be seen that FZ of the TIG welded samples consist of elongated grains of needle like α′ martensitic structure with equiaxed prior β grains. In HAZ region shown in fig 4.5 (b) needle like structure appears which becomes coarser as we move towards the FZ.

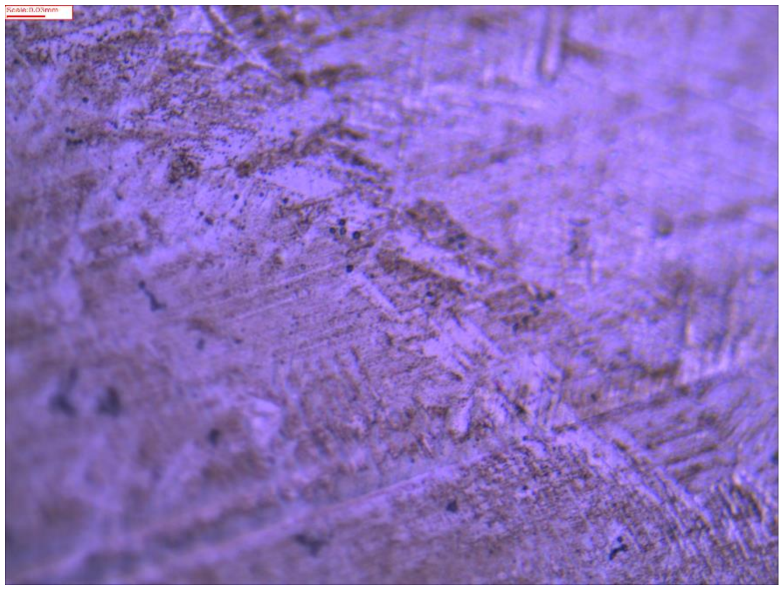


Fig. 4.5 (a)

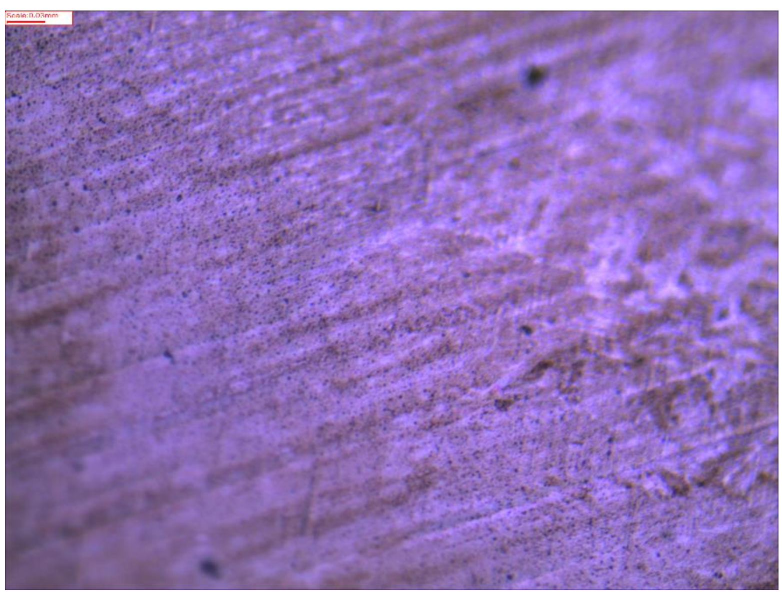


Fig.4.5 (b)

Fig. 4.5 (a) & (b) shows the FZ & HAZ microstructure of TIG welded samples

It can be concluded from the micro-structural analysis that grain growth and coarsening occurs in FZ & HAZ as heat is retained for longer periods because of low thermal conductivity of titanium [12].

4.3 Micro-Hardness

Micro-hardness was evaluated by Vickers Hardness Tester for BM, HAZ, FZ for laser and TIG welded samples. The difference in the microstructure as stated earlier in these regions leads to the difference in hardness values. The average hardness value observed at the base metal for this alloy is 345 HV which relates to the value reported in the literature [4, 19]. The highest hardness value is 395 HV which is observed in FZ of the laser welded sample. This increased hardness results due to the formation of α′ martensitic structure in the FZ of the laser welded sample. Gao et al [11], Squillace et al [23] and Cao et al [24]. The difference between the hardness values across the BM and FZ in laser welded samples is very large as the HAZ is small. In TIG welded sample this difference in hardness values is small because of a wider HAZ region. The average hardness value observed in FZ of the TIG welded sample is 370.45 HV which is 24.55 HV than the value observed in FZ of the laser welded sample. The decreased hardness in FZ of TIG welded sample is due to the presence of prior β grains in its microstructure. The figure 6 & 7 below show the variation in hardness values that occur across the BM, HAZ & FZ for laser and TIG welded samples respectively.

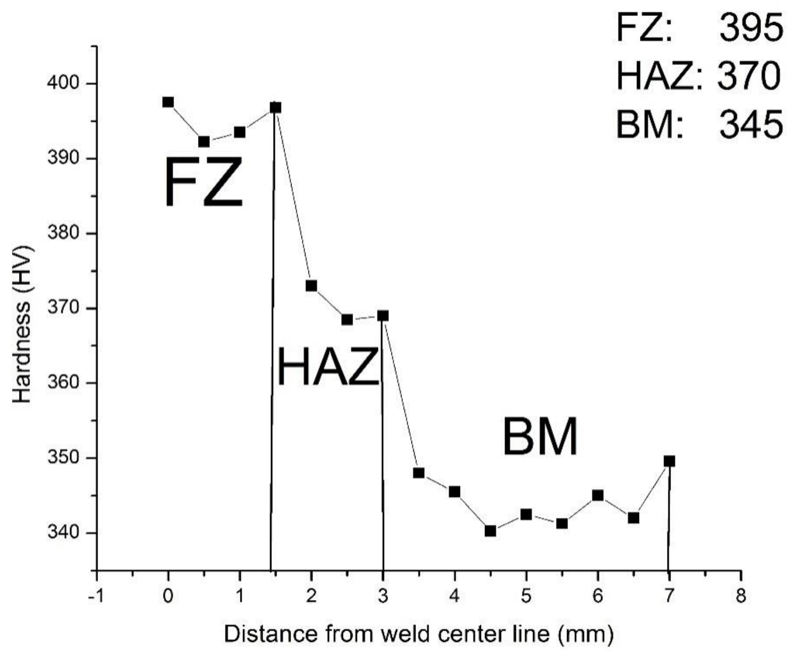


Fig. 4.6 Variation in Hardness values across BM, HAZ, FZ for LBW samples

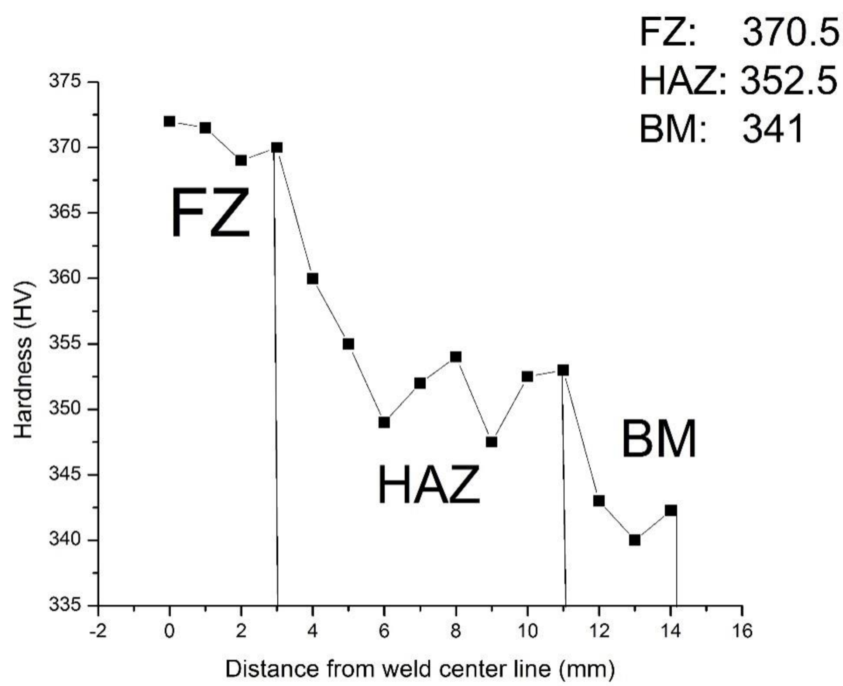


Fig. 4.7 Variation in Hardness values across BM, HAZ, FZ for TIG welded samples

4.4 Potentiodynamic Polarization Curves

Figure 4.8 below shows the comparison of the polarization curves obtained from BM, HAZ & FZ of the laser and TIG welded samples in 3.5% NaCl solution at room temperature. The values of corrosion potential (E_{corr}) and current density (i_{corr}) calculated from these curves is shown in the Table 4.1 below.

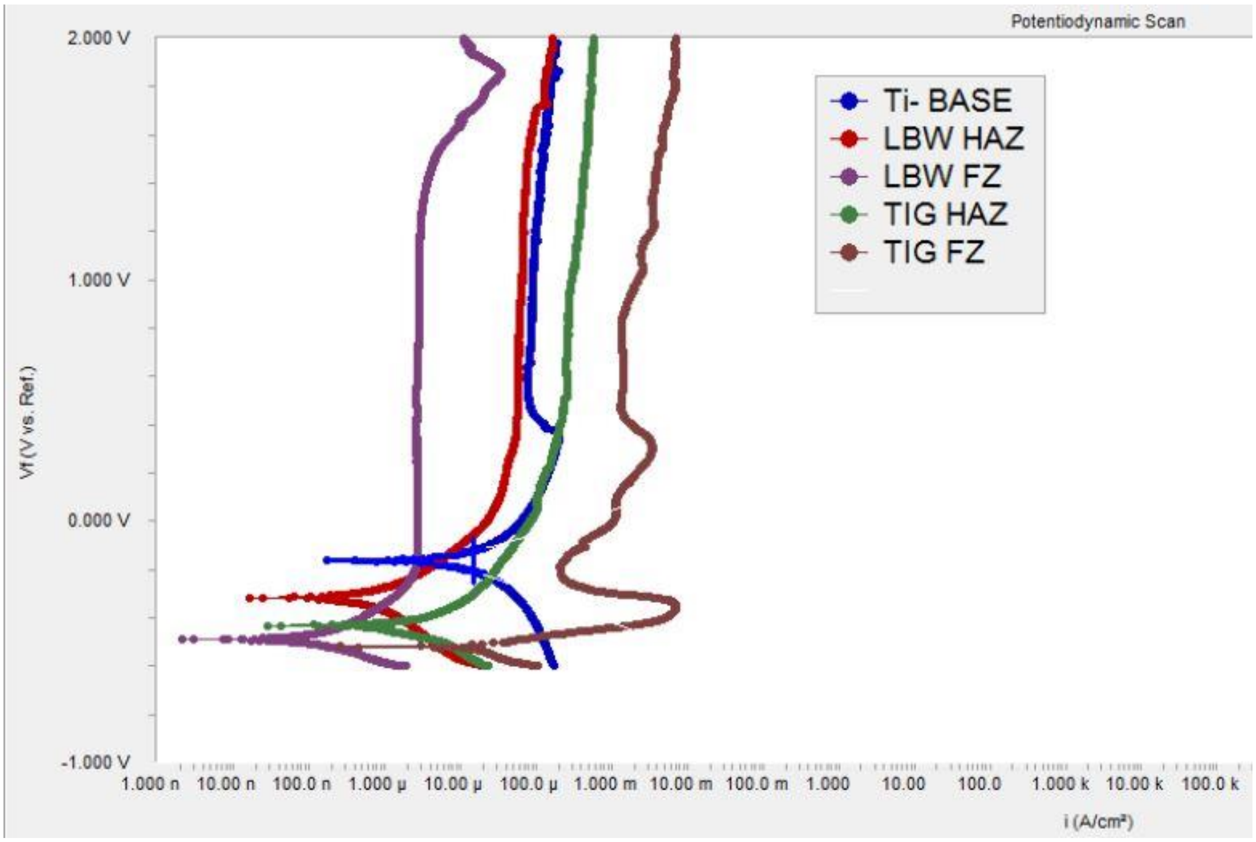


Fig. 4.8 Shows the polarization curves of BM, HAZ, FZ of LBW & TIG welded samples

Table: 4.1 Shows the E_{corr} and i_{corr} values

Sample Name	E_{corr} (V)	i_{corr} ($\mu A\ cm^{-2}$)
BM	-0.163	1.35
LBW HAZ	-0.317	1.01
LBW FZ	-0.489	0.17
TIG HAZ	-0.432	1.73
TIG FZ	-0.52	2.36

It is visible from the polarization curve of base metal that after reaching the corrosion potential (E_{corr}), the current density continuously increases up to approximately 0.4V after which it show a passive behavior due to formation of TiO_2. This passive behavior continues up to higher potentials. It is observed that corrosion potential (E_{corr})values of HAZ & FZ of both laser and TIG welded samples are lower than the E_{corr} values of base metal. It means that these regions start corroding early as compared to base metal at lower potentials. The FZ of laser welded samples start corroding at a lower potential but as the potential increases, a passive layer is formed. This layer is formed at a lower potential as compared to base metal and is the reason for FZ showing lower current density as compared to base metal. As stated earlier in the microstructure analysis, the microstructure of laser welded FZ consists of fine α′ martensitic structure without prior β grains. This micro-structural homogeneity leads to a higher corrosion resistance for FZ of laser welded samples. This type of behavior was also observed by Zhu etal[16] for laser welded Commercial Pure Titanium. The HAZ of laser welded samples also show a decrease in current density but this difference is small as the HAZ is very narrow in case of laser welding. The lowest corrosion potential (E_{corr}) is observed for FZ of TIG welded samples and the observed current density (i_{corr}) is highest. It starts corroding at a lower potential and shows a small passive region as the potential increases. As the potential increases further the passive film is broken and corrosion starts again. The FZ of TIG welded sample has microstructure consisting of α′ martensitic structure with equiaxed prior β grains. Due to this micro-structural in-homogeneity, it shows a lower corrosion resistance. The HAZ of TIG welded sample also shows a higher value of current density (i_{corr}).

Conclusions

Following conclusion can be drawn from our thesis:

- A change in microstructure was produced by the laser and TIG welding techniques.

- This change in microstructure was observed in XRD analysis and microstructure analysis which showed the formation α′ martensitic structure without prior β grains in case of FZ of laser welded samples and needle like α′ martensitic structure with equiaxed prior β grains in case of FZ of TIG welded samples.

- An increase in hardness values was observed for both laser and TIG welded samples. Laser welded samples showed a higher hardness value as compared to the TIG welded samples.

- Based on the E_{corr} and i_{corr} values the corrosion resistance of laser welded samples was found to be higher than the TIG welded samples and the base metal in 3.5% NaCl solution at room temperature.

Future recommendations

The future recommendations are as follows:

- For bio-medical applications Ti-5Al-2.5Sn alloy should be tested in stimulated body fluid solution.

- Comparison of corrosion properties of Laser and TIG welded Ti-6Al-4V and Ti-5Al-2.5Sn alloy should be done for different applications.

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