

EXTRACTION, PROCESSING AND

FAILURE MECHANISMS OF

TITANIUM AND ITS ALLOYS

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ABSTRACT

In this paper, the different factors that could affect titanium and titanium alloys are talked about. It is divided into two parts, the first part discussing the extraction, processing and fabrication processes and the second part discussing limitations and potential defects of titanium. The first part begins with the basic properties of titanium and how it is advantageous over other metals. Next, the extraction process of titanium using Kroll process is explained along with the different refinement processes used to refine titanium. Then, the different types of alloys of titanium and how they vary structurally is talked about. Lastly, the different machining and fabrication processes and the casting process is explained in detail. The second part of the paper focuses on the defects of titanium and its alloys. It starts with the environmental conditions that could hamper the health of titanium followed by how things like corrosion and welding defects could affect titanium. The different types of corruptions and welding defects that occur in titanium and its alloys are discussed as well along with a few methods that could be used to prevent corrosion and these defects are recommended. Lastly, a titanium alloy, Ti-6Al-4V is discussed with regards to different mechanisms of failure associated with the alloy.

PART 1: EXTRACTION, PROCESSING, MACHINING AND FABRICATION

1.1 INTRODUCTION

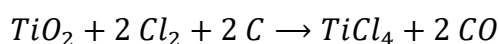
Titanium is a metal that has very high strength. Its strength and toughness are comparable to that of steel while it weighs nearly half that of steel. As a result, it is a very desirable metal in cases where high strength but low weight is required. But the process of extraction of titanium is very expensive and subsequently it is used for highly advanced applications where cost is not a critical factor. Hence, it is used very widely in aerospace, marine, chemical, biomedical industries and also in some sports. Titanium also has many other desirable properties such as high resistance to corrosion, high specific strength, low specific gravity and has non-magnetic properties. In this section, the process of extraction of titanium is discussed. Along with that, the properties of the different types of titanium alloys are talked about. Lastly, the different fabrication processes for the same are discussed.

1.2 EXTRACTION

The process of extracting titanium (Yang and Hlavacek, 2000) begins with the extraction of its ore, rutile. Ore rutile is also known as impure titanium(IV) oxide and is given by the formula TiO_2 . When rutile is processed in order to obtain titanium and the final titanium obtained is in the form of titanium sponge. The process used for the same is known as Kroll Process. This process involves three major steps:

- **Conversion of rutile to titanium(IV) chloride**

In this process, the ore rutile is heated up along coke and chlorine gas is passed through it. This can be given by the equation,



During this process, the ore rutile is heated up to a temperature of about 1000 °C.

As a result, the main product obtained from this process is titanium(IV) chloride, which is typical covalent chloride and is a colourless liquid. This also gives a biproduct of carbon monoxide. But beside carbon monoxide, other products such as carbon dioxide and carbonyl chloride are produced as well.

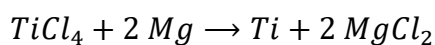
- **Fractional Distillation**

Other than titanium, the rutile ore has other metals in it as well. As a result, the chlorination process causes the formation of other metal chlorides in addition to titanium(IV) chloride. Hence, it is important to separate the titanium(IV) chloride from other metal chlorides. For this process, fractional distillation is used. In argon and nitrogen atmosphere, fractional distillation can be used to separate titanium(IV) chloride from other metal chlorides effectively. The separated titanium(IV) chloride is then stored in completely dry tanks. This is because when it comes in contact with moist air, it reacts with the moisture to give titanium(IV) oxide and fumes of hydrogen chloride.

- **Reduction of titanium(IV) chloride**

In this process, the titanium(IV) chloride in the form of liquid or vapour is reduced using either magnesium or sodium. This is done in an inert argon atmosphere at about 1000 °C. The titanium(IV) chloride is passed into a reaction vessel that contains liquid magnesium or sodium. The process of reduction is very slow and it takes about two days for the reaction to complete, followed by cooling process which takes a couple of days to

complete. At the end of the reaction, the products obtained are titanium and magnesium chloride. The reaction for the same can be seen below.



When the products obtained cool down, they are crushed and dilute hydrochloric acid is added to the mixture in order to remove the excess magnesium in the mixture by forming more magnesium chloride. The magnesium chloride is then easily removed using water as it completely dissolves in water. Hence, it leaves the titanium in the end.

- **Limitation**

The process of extracting titanium is very expensive compared to other metals. This is because it cannot be extracted by simply using carbon as a reducing agent as the titanium reacts with the carbon to form titanium carbide, which is far from pure titanium and also causes the metal to be very brittle.

1.3 PROCESSING

The processing of titanium is an important step after formation of the sponge. This process begins with the melting of titanium to form alloys. The most common method used for this is the vacuum arc refining (VAR) process (Karimi-Sibaki et al., 2022). Here, the titanium sponge is blended together with alloying elements and these are hydraulically pressed together in order to form small blocks known as briquettes. These briquettes are then welded together to form a 'stick' or a first melt electrode. The electrode is then put in the VAR furnace in order to produce the ingot. The electrode is held in the furnace by a stub and DC current is passed through the electrode. The molten electrode falls and forms an ingot at the bottom, which comprises of two layers, solid ingot below and molten pool of ingot on top. The

solidification is assisted using water-cooled copper crucible. This process is repeated two or three times to attain a good level of consistency throughout the material. The homogeneity and soundness of the ingot can also be easily ensured by altering the melting variables such as melting rate, molten pool depth, stirring etc. A schematic diagram of a VAR furnace is shown below in Fig. 1.

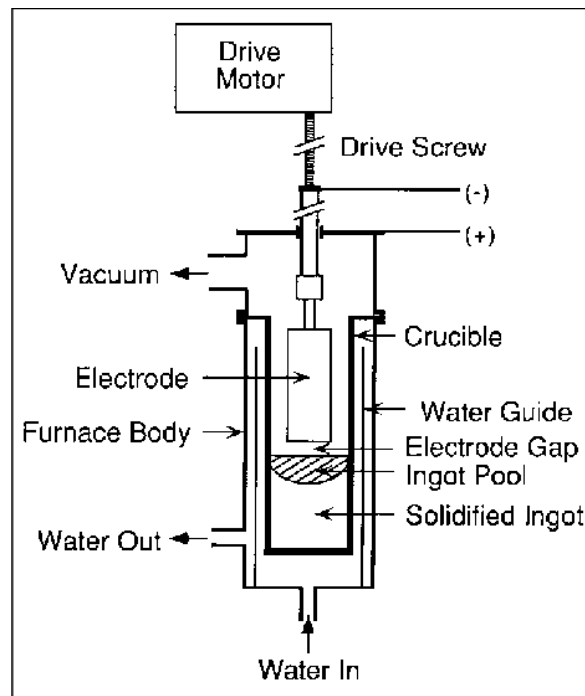


Fig. 1: Schematic Diagram of Variable Arc Refining Furnace (Melgaard et al., 1998)

The other melting processes that are used to form titanium and its alloys are electroslag refining (ESR) where the electrode is dipped into a pool of slag that is heated using AC current (Duan et al., 2019), plasma arc melting (PAM) where the metal is melted in a hearth using a heat source such as plasma torch (Blackburn and Malley, 1993), electron beam melting (EBM) which is similar to PAM uses electron beams to melt the metal and induction skull melting where a water-cooled copper crucible is used and the metal is charged inside the crucible using induction applied by magnetic field (Zhang et al., 2018).

1.4 TITANIUM ALLOYS

The titanium alloys can be majorly classified into three groups. These groups have different crystal structures and properties. This allows for manipulation of the heat treatments to produce different alloy microstructures to suit the required mechanical properties.

- **Commercially pure (CP) titanium alpha and near alpha titanium alloys-**

These are generally non-heat treatable and weldable. They have good creep resistance at high temperatures along with good notch toughness. They also have medium strength but good corrosion resistance. They form HCP structure. These are highly used in the aircraft industry, for heat exchangers, surgical implants, high pressure cryogenic vessels etc.

- **Alpha-beta titanium alloys-**

Unlike CP titanium, these are heat treatable and have good forming properties. They also have medium to high strength and good creep strength. Their microstructure depends on the chemical composition, processing history and heat treatments.

- **Beta titanium alloys-**

Beta titanium alloys are heat treatable and are readily formable. They have very high strength but are brittle and have low ductility. They possess BCC crystal structure. Beta titanium alloys have excellent corrosion resistance and combustion resistance as well for some alloys. But the major disadvantages of Beta titanium alloys are that they have a low processing window and high formulation cost.

1.5 MACHINING AND FABRICATION

For the shaping and manufacturing of products made using titanium and its alloys, most of the products are mechanically deformed by the processes listed below-

- **Forging**

Titanium alloys have much higher flow stress than aluminium alloys or steel. Hence, they require high forging pressure and capacity.

- **Rolling**

Titanium sheets are usually pack rolled in order to avoid surface oxidation. To prevent sheet bonding between individual planks, parting agents are added. These sheets of rolls are used to produce large cylinders for fan casing and pressure vessels.

- **Machining**

When compared to steel and aluminium alloys, titanium and its alloys are relatively more difficult to machine using methods such as drilling, turning, milling etc. titanium also has lower thermal conductivity and hence reducing tool life in case of welding. If the surface integrity of the tools are lost, it drastically affects the fatigue of the tool.

- **Powder metallurgy**

Titanium powder metallurgy parts are made by pressing and sintering. The production of titanium powder is very difficult because of its high reactivity with oxygen and hence this process is very expensive.

- **Superplastic forming and diffusion bonding**

This process is very desirable because of its ability to produce complex and light weight components with high stiffness and integrity. Here, a stop-off agent is used for bonding of regions of the sheet, which is followed by pressurisation of separate unbonded regions

of the sheet. Superplastic forming and diffusion bonding also reduces the number of production steps along with the number of extra components needed such as bolts and fasteners. A major disadvantage of this process is that it is very expensive and it cannot be used for critical load bearing structures.

1.6 CASTING

In the case of titanium and titanium alloys, casting accounts for a very small number of products used. Titanium castings are generally near net shaped products. As a result, there is minimum metal waste, which occurs during mechanical processing and machining. Titanium casting can majorly be classified into the following:

- **Conventional casting**

This is useful to produce intricate shapes with good surface finishing. Here, instead of using sand as the mould, rammed graphite is used because of its minimal tendency to react with molten titanium.

- **Investment casting**

Here, a duplicate model of the part or structure is created with wax, using engineering drawing of the specific part. The wax structure is then dipped into a ceramic slurry until a shell forms around it. Lastly, the wax is melted out of the shell and the molten metal is filled into it. This gives a final product with accurate dimensions while being highly cost effective (JC Casting, 2021). Hence, it is also most widely used titanium casting method. Fig. 2 below shows the process of investment casting.

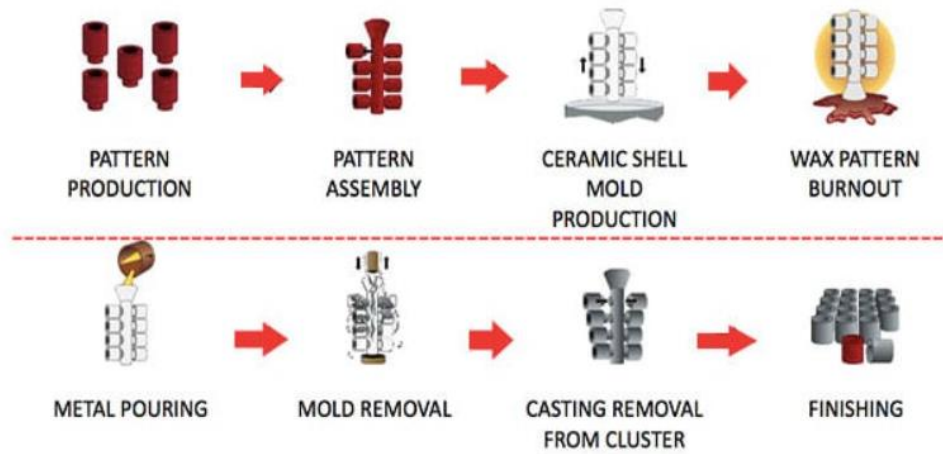


Fig. 2: Investment Casting Process (JC Casting, 2021)

- **Vacuum die casting**

This method is highly useful for achieving high quality parts. Vacuum is used during molten metal is injected and this reduces the gas entrapment in the metal and hence, decrease the porosity in the casting (Larsen and Colvin, 1999).

PART 2: LIMITATIONS AND POTENTIAL DEFECTS

2.1 INTRODUCTION

When compared to other metals, titanium and its alloys are relatively immune to the environmental conditions it is present in. Corrosion in titanium alloys takes place very slowly if at all when the conditions are perfect. That being said, there are certain factors that may influence the health of the metal. In certain environments, the oxide layer formed on titanium may vary and this could affect how it reacts to external conditions. This may also lead to corrosion of titanium if not taken care of. There may also be defects to the surface of the metal during the fabrication process. Also, defects might be introduced during the welding of titanium. This section of the report is an analysis of the types of corrosions and defects that may occur in titanium and the methods that can be used to prevent the same.

2.2 LIMITATIONS IN SPECIFIC ENVIRONMENTS

Titanium and titanium alloys are generally known to have great resistance to environmental conditions compared to most other metals in general. This is because a protective oxide film forms on the surface of the metal which is very adherent and stable. The film forms over the surface of the metal because titanium is very reactive and has a high affinity for oxygen. As soon as the fresh metal surface comes in contact with the air or moisture, the surface oxide layer forms instantaneously. For this very same reason, if the oxide film is damaged due to any circumstance, it has the capability to self-heal as long as there is some oxygen or moisture in the air.

The type of oxide layer formed on titanium and its alloys may vary. This is mainly because of the environmental conditions around the metal during formation of the oxide layer. As a result, things like the nature, composition and thickness of the oxide layer may vary vastly. In general, the most commonly formed oxide in most environments is TiO_2 , but the layer might also be a mixture of multiple oxides such as TiO_2 , Ti_2O_3 and TiO . The type of oxide layer formed also varies depending on the temperature of the environment. At higher temperatures, chemically resistant and highly crystalline form of TiO and lower temperature oxidation usually tends to form a more amorphous form of TiO known as anatase.

2.3 CORROSION

That being said, in conditions where a source of oxygen is absent, the protective oxide layer fails to regenerate and this causes corrosion of titanium. The different types of corrosion that are observed in titanium and its alloys are general corrosion, crevice corrosion, anodic pitting, hydrogen damage and stress-corrosion cracking (Total Materia, 2001).

- **General corrosion**

This is caused due to the presence of an aqueous medium in the environment in general.

It is characterised by a relatively uniform attack on the surface of the metal. It is usually caused due to variation in the corrosion rates throughout the surface of the metal.

- **Crevice corrosion**

Crevice corrosion occurs in tight crevices and is a form of local attack. In the case of titanium, it takes place when the crevice is exposed to solutions containing hot chloride, bromide, iodide, fluoride or sulphate at over 70 degrees Celsius. These crevices may be formed due to multiple reasons such as joints caused by welding, gasket-metal flange etc.

- **Pitting**

Pitting is a phenomenon that takes place on the surface of the metal when there is a potential difference. It occurs when the potential of the metal exceeds the anodic breakdown potential of the layer of oxide film. It is a localised corrosion that takes place on the openly exposed metal surface in the absence of any crevices. The same can be seen in Fig. 3.

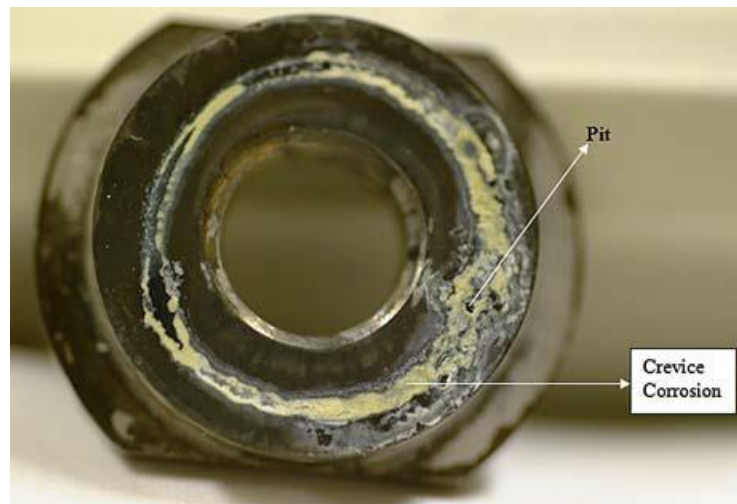


Fig. 3: Crevice Corrosion and Pitting in Titanium (Abdulsalam, 2006)

- **Hydrogen damage**

In cases where galvanic couple or cathodic charging causes hydrogen to evolve on the surface of the metal, titanium and its alloys are used extensively. Even though titanium proves to be very effective in such conditions, the hydrogen present there has a high likelihood of causing hydrogen embrittlement to the metal. This mainly happens when anhydrous hydrogen gas is used at higher temperatures and pressures as it does not have any oxygen or moisture to form the protective oxide layer.

- **Stress-corrosion cracking (SCC)**

Stress corrosion cracking (Joseph et al., 2022) is a material failure process that takes place due to a combination of multiple events. It usually occurs in the presence of a susceptible

alloy, tensile stress and a corrosive environment. This is a phenomenon that can be controlled or reduced by altering the metallurgical characteristics of the metal in use or by makeup of the environment. The stress required for this to take place may come as a result of residual stresses during the fabrication process or when external loads are applied to it. Fig. 4 below shows a titanium propellant tank failure due to stress-corrosion cracking.



Fig. 4: Stress-corrosion Cracking in Titanium Propellant Tank for Vega Rocket (The European Space Agency, 2014)

2.4 DEFECTS

2.4.1 Defects in fabrication

Titanium and its alloys are usually used in high end machinery due to its high cost of production. As a result, defects during fabrication and production need to be minimized and in case there are defects, these need to be identified in order to make sure that the object or machine does not fail. Most of the defects relating to titanium occur on the surface of the metal. A few of these defects are classified below (Advanced Refractory Metals, no date).

- **Over-corrosion**

As stated in the section above, corrosion could lead to be a massive defect and cause material failure. The most common type of corrosion that occurs in titanium alloys is pitting which causes the surface of the metal to be uneven. This is caused due to the presence of a potential difference on the metal surface.

- **Ash hanging**

This is a phenomenon in which an oxide layer remains attached to the surface of a titanium alloy after it is acid washed. This is mainly caused due to two reasons, firstly, excessive ash deposition during the pickling process and secondly if the metal is not washed properly after pickling. If this defect is not taken care of, it may affect the properties of the alloy such as adhesion, appearance and corrosion resistance of the oxide coating.

- **Streaks**

Streaks is a phenomenon that occurs on the surface of the titanium alloy. This usually occurs due uneven reaction. It can be easily avoided by taking appropriate measures

during the pickling process. This can be done by shaking the parts during pickling and by reducing the temperature of the pickling solution.

- **Incomplete oxide scale**

This is a defect in which the oxide scales are not completely removed from the surface of the metal. This can be caused multiple reasons such as failure of the pickling solution, insufficient molten salt treatment time and poor degreasing.

2.4.2 Defects in welding

Since titanium and its alloys are highly reactive to oxygen, they need special environments for the welding process. Welding has to be carried out in the absence of oxygen and hence air. For this purpose, titanium and its alloys are welded either in vacuum or by using certain shielding gases. The shielding gases that are usually used are argon or helium.

Even with all the precautions, there might be some defects associated with the welding of titanium. The most commonly seen welding defects are weld metal porosity, embrittlement and contamination cracking. **Weld metal porosity** is the most common one out of the three. This occurs when there are gas bubbles trapped between the dendrites during the solidification process. **Embrittlement** happens due to oxygen, nitrogen or hydrogen contamination during welding process. This usually occurs at temperatures above 500 °C and can be prevented by effective shielding. Lastly, **contamination cracking** is a phenomenon that occurs when there are iron particles in the surface of the component used for welding. This can also happen if there is steel fabrication process in the vicinity. As a result, the corrosion resistance of the metal reduces drastically. This can be avoided using various methods such as not fabricating titanium and steel close by, covering components from airborne dust

particles, not using same tools used for steel, handling clean components with dirty gloves etc.

2.5 RECOMMENDATIONS

2.5.1 Corrosion resistance

The problem of corrosion in titanium and its alloys can be reduced by using various methods.

A few of these are listed below:

- Use anodizing or thermal oxidation to increase the thickness of the oxide film.
- Use anodic protection by anodically polarizing the titanium alloy.
- Surface treatment by applying surface coating using precious metals.
- Alloying the titanium with other elements.
- Creating oxide film stabilization.
- Stabilizing the oxide film by using oxidising species as inhibitors to the reducing conditions

2.5.2 Reducing or eliminating defects

The defects in titanium and its alloys can be reduced or completely eliminated by using the following methods:

- Making sure that there are no ash hanging on the metal surface
- Shaking the parts during pickling
- Reducing the temperature of the pickling solution

- Avoiding steel fabrication in the presence of titanium nearby
- Using separate welding tools for titanium and steel
- Avoiding using dirty equipment near clean titanium

2.6 Ti-6Al-4V TESTING

Ti-6Al-4V is a titanium alloy that mainly comprises of three metals, titanium, aluminium and vanadium. It is an alpha-beta titanium alloy. It has a low density along with high specific heat and great resistance to corrosion. As a result, it is one of the most highly used titanium alloys and is greatly used in the field of aerospace along with biomechanical and biomedical applications.

Ti-6Al-4V is poor thermal conductivity at room temperature. This leads to poor machinability of the alloy. As a result, Ti-6Al-4V is vulnerable to cold dwell fatigue (Xu et al., 2020) which is a phenomenon in titanium in which stress holds at moderate temperatures and this leads to a reduction in its cyclic life.

Wojtaszek et al. (2013) conducted tests to determine the quasi-static and dynamic tensile properties of Ti-6Al-4V alloy. For this, they used a non-contact material independent measuring system known as the ARAMIS system that provides accurate values for 2D displacement and surface strain rate. They conducted the tensile tests at different testing velocities and found out that the elastic modulus and fracture strength of the alloy were 104 GPa and around 1000 MPa respectively. Fig. 5 shows the stress-strain curve for the same at the different test velocities.

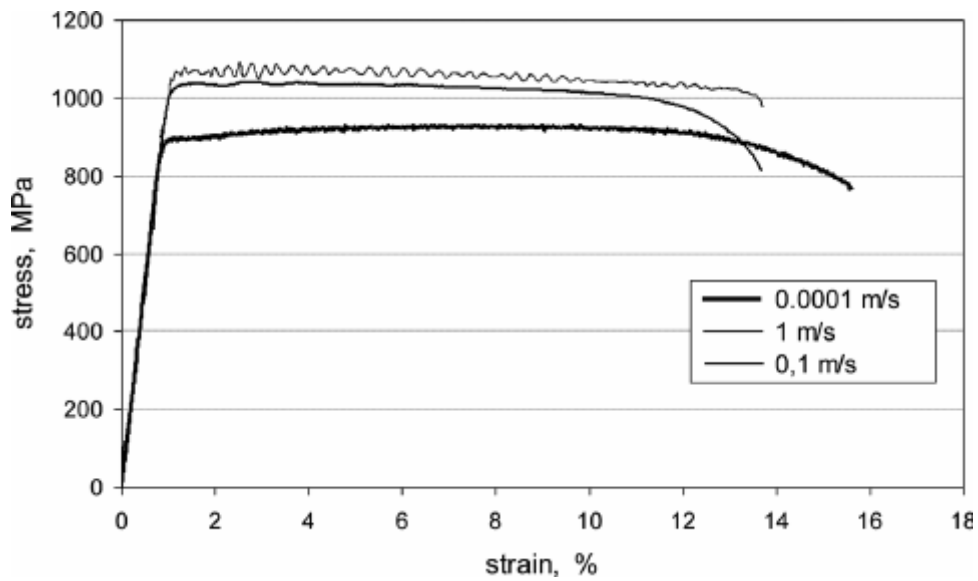


Fig. 5: Stress-Strain Curve for Ti-6Al-4V alloy (Wojtaszek et al., 2013)

They discovered that the alloy under the dynamic conditions exhibited higher fracture strength values than under quasi-static conditions. Any change to the strain rate did not affect the elastic module of the alloy either. They also discovered that the test specimen showed dimples on the surface which means ductile rupture.

Zhang et al. (2016) tested the failure of Ti-6Al-4V under uniaxial tensile loading conditions. They determined that failure often occurred due to nucleation, growth and coalescence of voids at the interface between different phases of the material. Two different failure modes were determined, namely shear band and vertical split band. But when the specimen was heat treated, it only exhibited vertical split failure. Lastly, the main reasons for failure were predicted to be due to microstructure level inhomogeneity and incompatible deformation between the different phases of the tested specimen.

CONCLUSIONS

This paper is divided into two sections. In part 1, the process of extraction of titanium from rutile is explained. Then, how vacuum arc refining is used to refine the titanium is discussed in detail along with the other forms of refining such as electroslag refining, plasma arc melting and electron beam melting. Next, the different types of titanium alloys along with their structural properties were discussed. Lastly, the different fabrication methods of titanium and its alloys such as forging, rolling, machining, superplastic forming and diffusion bonding etc. were talked about along with the different casting methods such as conventional, investment and vacuum die casting.

In part 2, the limitations of titanium and its alloys in certain environments is discussed. To understand this properly, things like how titanium reacts in the presence of air and how it forms different oxide layers are explained. Next, the different types of corruptions that titanium experiences are talked about such as general corrosion, crevice corrosion, pitting stress-corrosion cracking etc. Lastly, different types of defects such as ash hanging, streaks, incomplete oxide scales etc. that may occur during the fabrication process are discussed along with the defects that could be caused by welding. Some recommendations and methods for preventing these defects and corruptions from happening in titanium and titanium alloys are discussed as well. Lastly, a titanium alloy Ti-6Al-4V and its mechanisms of failure are talked about.

REFERENCES

- Yang, F., Hlavacek, V. (2000) *Effective Extraction of Titanium from Rutile by a Low-Temperature Chloride Process*, AIChE Journal, Volume 46, Issue 2, February 2000, Pages 355-360
- Karimi-Sibaki, E., Kharicha, A., Vakhrushev, A., Abdi, M., Wu, M., Ludwig, A., Bohacek, J., Preiss, B. (2022) *Numerical Modeling and Experimental Validation of the Effect of Arc Distribution on the As-solidified Ti64 Ingot in Vacuum Arc Remelting (VAR) Process*, Journal of Materials Research and Technology, Volume 19, 2022, Pages 183-193
- Melgaard, D.K., Williamson, R.L., Beaman J.J. (1998) *Controlling Remelting Process for Superalloys and Aerospace Ti Alloys*, JOM: the journal of the Minerals, Metals & Materials Society, March 1998
- Duan, SC., Shi, X., Wang, F., Zhang, FC., Sun, Y., Guo, HJ., Guo, J. (2019) *A Review of Methodology Development for Controlling Loss of Alloying Elements During the Electroslag Remelting Process*, Metallurgical and Materials Transactions B 50, 3055–3071 (2019). <https://doi.org/10.1007/s11663-019-01665-2>
- Blackburn, M.J., Malley, D.R. (1993) *Plasma Arc Melting of Titanium Alloys*, Material and Design, Volume 14, Issue 1, Pages 19-27
- Zhang, L.-C., Liu, Y., Li, S. and Hao, Y. (2018), *Additive Manufacturing of Titanium Alloys by Electron Beam Melting: A Review*, Advanced Engineering Materials, 20: 1700842. <https://doi.org/10.1002/adem.201700842>
- JC Casting (2021) *What is Titanium Investment Casting*. Available at: <https://www.investmentcastingpci.com/blog/what-is-titanium-investment->

[casting/#:~:text=Titanium%20investment%20casting%20is%20a,left%20to%20dry%20and%20harden.](#)

- Larsen, D., Colvin, G. (1999) *Vacuum-Die Casting Titanium for Aerospace and Commercial Components*, JOM 51, 26–27 (1999). <https://doi.org/10.1007/s11837-999-0089-4>
- Total Materia (2001) *Corrosion of Titanium and Titanium Alloys*. Available at: <https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&LN=PT&NM=24>
- Abdulsalam, M.I., (2007) *Crevice Corrosion of Titanium in High Temperature-Concentrated Chloride Environments*, Journal of Materials Engineering and Perform 16, 736–740 (2007). <https://doi.org/10.1007/s11665-007-9090-7>
- Joseph, S., Kontis, P., Chang, Y., Shi, Y., Rabbe, D., Gault, B., Dye, D. (2022) *A Cracking Oxygen Story: A New View of Stress Corrosion Cracking in Titanium Alloys*, Acta Materialia, Volume 227, 1 April 2022, 117687
- The European Space Agency (2014) *Tank Failure Due to Stress Corrosion Cracking*. Available at: https://www.esa.int/ESA_Multimedia/Images/2014/12/Tank_failure_due_to_stress_corrosion_cracking
- Advanced Refractory Metals (no date) *Defects on The Surface of Titanium Alloys*. Available at: <https://www.refractorymetal.org/defects-on-the-surface-of-titanium-alloys/>
- Xu, Y., Joseph, S., Karamched, P., Fox, K., Rugg, D., Dunne, F.P.E., Dye, D. (2020) *Predicting Dwell Fatigue Life in Titanium Alloys Using Modelling and Experiment*, Nature Communications 11, Article Number: 5868 (2020). <https://doi.org/10.1038/s41467-020-19470-w>

- Wojtaszek, M., Sleboda, T., Czulak, A., Weber, G., Hufenbach, W.A. (2013) *Quasi-Static and Tensile Properties of Ti-6Al-4V Alloy*, Archives of Metallurgy and Materials, Volume 58, Issue 4, 2013
- Zhang, X.-C., Zhong, F., Shao, J.-B., Zhang, C.-C., Hou, N.-X., Yuan, G.-J., Tu, S.-T. (2016) *Failure Mechanism and Mode of Ti-6Al-4V Alloy Under Uniaxial Tensile Loading: Experiments and Micromechanical Modeling*, Materials Science and Engineering: A, Volume 676, 2016, Pages 536-545, ISSN 0921-5093, <https://doi.org/10.1016/j.msea.2016.09.019>.