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**EXTRACTION, PROCESSING, AND FAILURE MECHANISMS OF
TITANIUM AND ITS ALLOYS**

MECHANISM OF MATERIAL FAILURE (ACEA7010)

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ABSTRACT

This abstract focuses on the numerous methods used in commercial manufacturing as well as the extraction and processing of titanium. Due to their outstanding qualities, including their high strength-to-weight ratio, resistance to corrosion, and biocompatibility, titanium and its alloys are widely employed in a variety of industrial applications. In addition, the failure mechanisms of titanium and its alloys, such as fatigue, stress corrosion cracking, and hydrogen embrittlement, are investigated. These mechanisms have a big impact on the functionality of titanium components. To create new and better materials for a variety of applications, it is essential to comprehend the extraction, processing, and failure mechanisms of titanium and its alloys.

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1.Introduction

The prime concern of this paper is to investigate the failure mechanism of titanium and its alloys along with understanding the challenges related to the extraction and processing of this specific metal. Description of the properties and the key factors related to the difficulties in processing and fabrication are structured with detailed information. In addition, limitations of titanium in any specific environment and the explanation of key factors related to it have been structured adequately.

2.Part One

2.1 Properties of the titanium

The chemical behavior of titanium and its alloy shows diverse similarities with silica. This chemical element has the atomic numbers 22 and 47.90 of atomic weight. It is a transition metal lightweight with greater resistance power. This metal is not found in its pure form but as oxides such as rutile (TiO_2). Pure titanium is not intended to dissolve in water but in several concentrated acids (Jiang et al. 2020). An oxide coating formed by titanium leads to "corrosion resistance" which is passive and provides effective protection. The oxidation state of it of $3+$ and $2+$ is less stable whereas the $4+$ state is much more stable. The element, while heating burns in the air in order to obtain the formation of dioxide (TiO_2) with combined halogens. It involves in reduction of water vapor for the formation of hydrogen and dioxide. Titanium reacts in that way with concentrated acids (Liao et al. 2021). However, it combines with chlorohydrin acid to form dichloride. It absorbs hydrogen to form the TiH_2 and nitride, and TiC is formed. Its melting point is 1600°C and its boiling point is 3287°C .

Five major properties of Titanium can be subjected to its excellent strength, high rate of corrosion resistance, low modulus of elasticity, better welding ability, and heat-treatable properties. Added the aluminum and the vanadium effectively increases the hardness of the alloy matrix that improves both the mechanical and physical properties of this material. Titanium is highly reactive with nitrogen, oxygen, hydrogen, and carbon (Wang et al. 2020). It has higher toughness and strength. However, the extraction process of this metal is so difficult and expensive. Advanced

application of this material in its wrought forms. Often its nonmagnetic property enhances its operational areas. Due to their special properties, the alloys are widely used in aerospace, chemical, marine, sports, and biomedical applications. Additionally, it has to be mentioned that this particular metal behaves improperly in high temperatures that ranges above 400° C as its strength begin to lose.

2.2 Challenges in the processing of titanium and its alloys

The primary disadvantage of titanium is its high reactivity which states that it requires different management during each stage of its production. The "Kroll process" is used in the extraction of this metal where it introduces diverse impurities. Three removals of these impurities are highly impossible at first but deploying the process of EBCHR effectively works which is so expensive. It is not suited to the higher range of temperatures (Zhang et al. 2022). During the machining of these alloys' utilization of appropriate cutting tools and speed. Although it does not comprise any severe mitigation requirements during its extraction process the main issue is subjected to the well-publicizing ores of the titanium.

Major difficulties in the preparation of pure titanium are subjected to its reactivity property. Extraction of titanium is not easily done with the application of the common method of oxide reduction with carbon as a daily production of a very stable carbide is observed. The metal shows its reactivity toward nitrogen and oxygen at elevated temperatures. In the "kroll process", an ore of this metal, such as rutile (TiO_2) is treated at higher heat with chlorine and carbon to yield a tetrachloride form of this melt (TiCl_4) (Shokrani et al. 2019). Then that is distilled fractionally to eliminate the impurities. Impurities can be exemplified as ferric chloride (FeCl_3). The titanium tetrachloride is then reduced at about 1,500 °F with the application of magnesium in molten form in a specific atmosphere. This results in the formation of metallic titanium as a form of spongy mass. From that, the excess amount of magnesium chloride and magnesium can be easily removed by the process of volatilization at 1,800 °F. Then the sponge may be fused in an argon atmosphere in an electric arc. The extremely pure form of titanium can be produced by deploying the vaporizing process to the tetrachloride form of titanium, in laboratories (Doan et al. 2021). This specific form of titanium is in decomposing and very pure form in a vacuum on a hot wire.

Other major issues related to the processing of alloys of titanium include the machined surface quality, temperature of cutting, formation of bars, and tool wear which effectively increases the

final cost of the product. A mechanical process of machining is milling, which is used widely to create features free from 3D in materials that include polymers, metals, and ceramics (Sarikaya et al. 2021). The processes through which the machinability of this specific metal can be observed experimentally are orthogonal turning, machining, and milling.

2.3 Evaluating the material failure mechanism of titanium and its alloy

The "Fatigue failure" can be referred to a major failure type of engineering structure. Differently, factors have been studied on the "fatigue" of the titanium alloy and its components (Korkmaz et al. 2022). Some structures such as aircraft engines and "deep submersible pressure shells" that use materials of titanium alloy are subjected to the cyclic loads while operating and the duration varies due to the dead loads. When performing the "steady operation load process", there is the continuation in plastic strain for accumulation even being the stress level less than the "yield strength" (He et al. 2020). This specific phenomenon is termed creep which becomes the cause of a significant reduction of fatigue life. The "Creep-fatigue" can be significantly focused while operating in high-temperature. Two main reasons subjected to this problem are most of the materials creep at higher temperatures and another is the accelerated stage of creep exists only when the temperature is high and the creep failure occurs.

The determination of the machinability of titanium can be obtained by segmentation and chip morphology during the titanium alloy machining process. While the speed of cutting is lower often the chip discontinues but it shows aerated while the speed is made at a high speed. Therefore, the chip segmentation examination has taken place widely by application of thermodynamic theory in the area of chip formation (Sanguedolce et al. 2023). The "Hydrogen embrittlement" phenomenon of titanium is the most common. The failure mechanism of this phenomenon is termed "delayed failure". Within the stress concentration areas, it increases diffusion and creates defective forms at low stress.

Proper application of regression analysis technique for analyzing the oxidation characteristics of "near- α Ti alloy" by adding Ga, Al, Zr, Ta, and Si can be easily performed. For this particular test, the temperature must be controlled at 700 °C and the correlations can be obtained significantly (Gupta et al. 2022).

2.4 Critical examination

Based on analyzing all throughout the circumstances, it has been observed that the preparation process of pure Titanium has been found to be immanence difficult as the significant aspects of the reactivity in all throughout the contexts (Ao et al. 2023). It cannot be extracted from the common method that includes the reduction method of carbon and oxides as the stable form of carbide is readily produced in available throughout the contexts.

On the other hand, after extraction of the pure titanium, it has been observed that it is pure ductile and the density has been compared aligning with the iron and less than twice as dense as the aluminum that can be polished to a high rate of luster. This kind of metal possesses low thermal and electrical conductivity and is paramagnetic (Mruthunjaya and Yogesha, 2021). Moreover, this metal is also considered as excellent corrosion-resistance properties and the formation of a passive oxide surface film implications all throughout the process. It also resembles transition properties as analogous to the other metals of nickel and iron based on analyzing the refractory and hard properties. The combination of the low density with the high amount of strength creates useful properties that are helpful in possessing a number of applications based on real-life phenomenon that includes spacecraft and aircraft, missiles, along with the formation procedure of ships (La Monaca et al. 2021). It is also useful in the application of prosthetic devices as it does not react with bone and fleshy tissues.

3.Part Two

3.1 Limitations

As per the discussion in the above section, it has been seen that titanium and its alloys are well known for their corrosion-resistant property and mechanical property. Apart from these beneficial properties, there are several limitations of titanium and its alloys in significant environments. As per the view of Shokrani *et al.* (2019), the limitation contains in titanium and its alloys are:

Cost: The alloy of titanium and titanium itself is expensive compared to other utilized metals such as aluminum and steel. The reason for the high cost of titanium and its alloys is the complexity of refining and extracting titanium from its ores.

Low thermal conductivity: The thermal conductivity of titanium low than that of other metals like aluminum and copper. Therefore, the usage of titanium and its alloys is limited in applications where there is a requirement for high stiffness.

Low modulus of elasticity: Titanium and its alloys contain a lower modulus of elasticity compared to other metals such as steel and more. Hence, the alloys of titanium and titanium itself are not as stiff as steel. Therefore, due to this limitation titanium and its alloys cannot get used where high stiffness is needed.

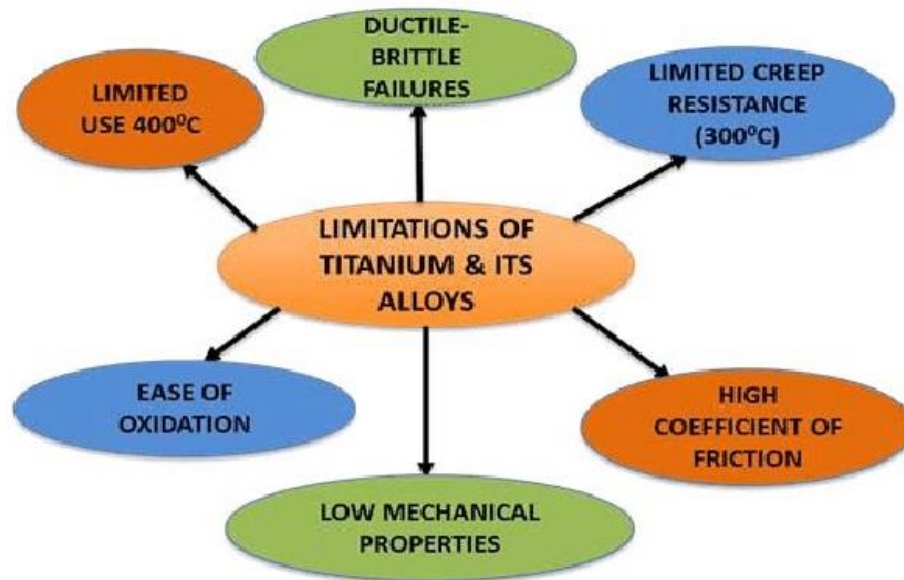


Figure 3.1: Limitations of Titanium and its alloys

(Source: Doan *et al.* 2021)

Susceptibility to hydrogen embrittlement: Titanium along with its alloys is susceptible to **hydrogen embrittlement**, which can emerge when the alloys of titanium and titanium itself are exposed to hydrogen at high-pressure or high temperatures. This can force the metals to become brittle as well as fail under stress.

Low machinability: As per the view of Zhang *et al.* (2022), there are a few complexities in machining titanium and its alloys because of their low thermal conductivity, high strength, and the tendency to work hardening during the process of machining.

Limited availability of alloys: The availability of alloys of titanium is limited than other metals such as aluminum and steel. Therefore, this limits its usage of its in specific applications such as where the properties of specified materials are needed.

The limitations of titanium and its alloys in specific environments are described in the above section.

3.2 Identification of potential defects

As per the view of Wang *et al.* (2020), during the fabrication and processing of components that are made from the usage of titanium and its alloys, several potential defects can occur. The potential defects that can get occurred during the fabrication process and processing of components are as follows:

Cracking: Because of its low ductility as well as great strength, titanium, along with its alloys are susceptible to cracking. This can happen during heat treating or welding, as well as during rolling, forging, or other operations of deformation.

Porosity: During the procedure of welding, casting, or other procedures where the substance is melted and then gets solidified, porosity may be introduced. This might damage the substance as well as can lessen its mechanical qualities.

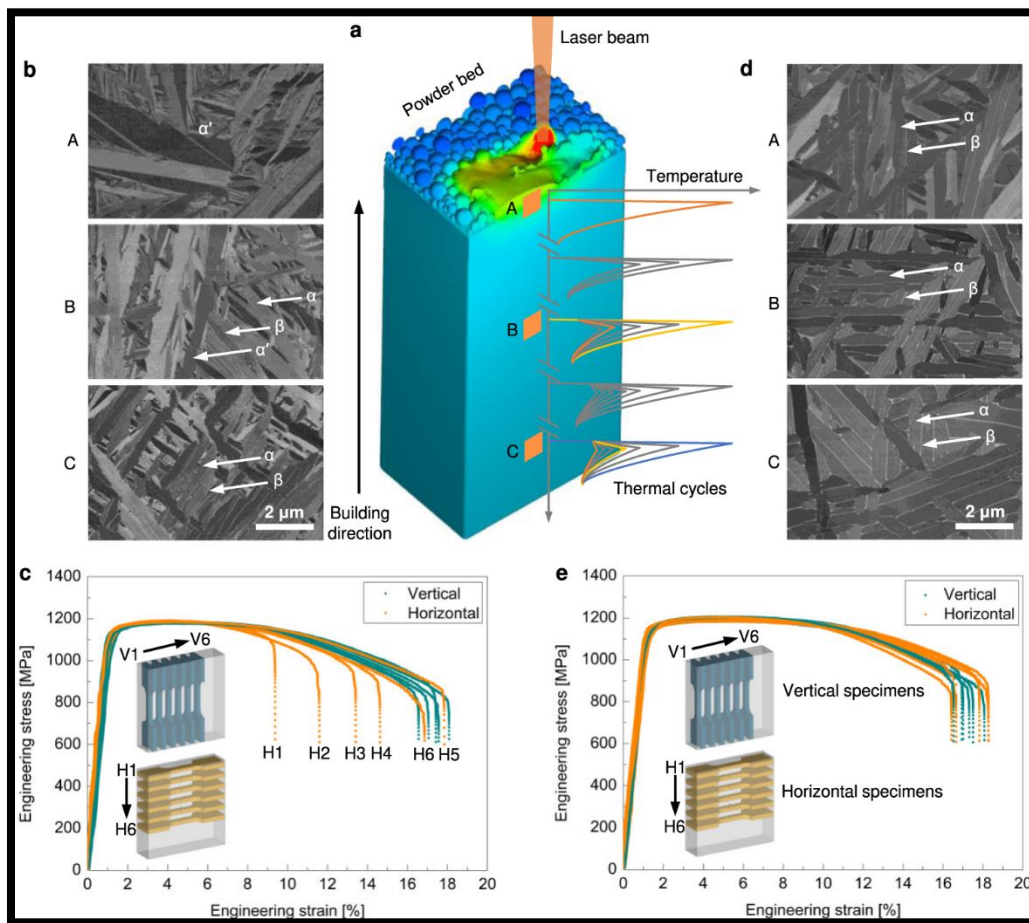


Figure 3.2: Defects during processing and fabrication of titanium and its alloys

(Source: Abhilash and Chakradhar, 2021)

Inclusions: foreign or Particle substances that can get added during fabrication and processing are known as inclusions. Significantly, where there are requirements for high-stress concentrations, they can dilute the substance as well as can lessen its mechanical properties.

Surface flaws: During the machining process or other finishing processes, surface flaws like nicks, scratches, and gouges may get introduced. These flaws may serve as stress concentrators and cause an early component failure.

Inadequate heat treatment: Inadequate heat treatment can cause changes to the material's mechanical characteristics and microstructure. Ductility, reduced toughness, or strength may be the outcome of this.

Contamination: The properties and performance of the material may be impacted by the presence of other foreign compounds or metals. For instance, oxygen or carbon contamination can lessen the corrosion resilience of titanium as well as of titanium alloys.

3.3 Correlation between potential defects identified with the actual practice

The correlation between actual practice and potential defects is dependent on various factors such as the particular alloy along with the process of manufacturing that is used, the type of defect, and the component's intended application. As per the view of Liao *et al.* (2021), In order to minimize the occurrence of risk of damage, it is essential to control the fabrication and processing of titanium along with the alloys of titanium. The potential defects including surface defects, porosity, cracking, incorrect heat treatment, inclusion, and contamination can get detected as well as get controlled via the measurement of proper quality control such as inspection, non-destructive testing, and process control. In addition to that, defects can get occurred because of numerous pf factors such as malfunction of equipment, human error, and variation in the properties of the materials.

Hence, it is necessary of containing a proper process in place for the identification as well as addressing the defects as soon as they occur such as the replacement or repairing of defective components, or changes in the process of manufacturing for the prevention of future defects. Furthermore, in titanium and its alloys, the correlation between actual defects and potential defects is complicated and also can get varies on the basis of several factors. Therefore, it is important to follow the appropriate measurement of quality control along with including the proper process for addressing and detecting defects. By using this mentioned procedure, the risk of occurring defects

in titanium and its alloys can be minimized and the reliability and performance of the titanium compounds can also be maximized.

3.4 Failure mechanisms of Titanium and its alloys

As per the view of Li *et al.* (2021), the failure mechanism of Titanium and its alloys includes various mechanisms. The various failure mechanisms are:

Failure due to fatigue: Failure due to fatigue happens when a component experiences cyclic stress or loading, which can lead to forming of cracks and spreading the cracks over time until the element breaks. Due to its high strength and low ductility, titanium along with its alloys are primarily prone to fatigue failure.

Creep failure: When a component is exposed to high stress and temperatures over an extended period of time, the material may deform gradually and ultimately fail. When compared to other metals, titanium and its alloys have a high creep resistance, but they are still susceptible to creep failure.

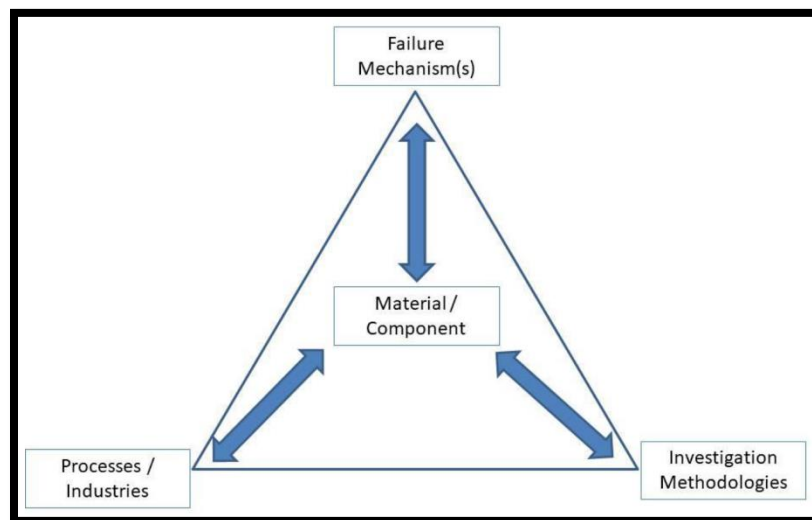


Figure 3.4: Failure mechanisms of Titanium and its alloys

(Source: Tu *et al.* 2022)

Failure due to corrosion: When an element is exposed to corrosive environments, the substance can deteriorate and lose its mechanical properties, leading to corrosion failure.

Wear failure: When an element is repeatedly subjected to abrasion or friction, wear failure happens. This can lead to the material wearing out over time and finally failing. Although titanium and its alloys contain excellent wear resistance, they are still susceptible to wear failure in

individual situations, such as those involving high contact stresses or disclosure to abrasive particles.

Overload failure: As per the view of Jiang *et al.* (2020), when a component is exposed to an excessive and abrupt load or tension, which could cause it to fracture or deform, overload failure happens. Despite having excellent toughness and strength, titanium and its alloys are still susceptible to overload failure if they are put under stresses or loads that are too great compared to their design tolerances.

3.5 Critical evaluation

In this project report, *the Extraction, processing, and failure mechanisms of Titanium and its alloys* have been discussed. In this second part of the project report, the effects, causes, and mechanisms of environmental degradation of titanium and its alloys are discussed. The failure mechanisms of titanium along with its alloys are also described in this section of the second part. After performing the analysis, it can be critically stated that there are certain limitations to using titanium and its alloys as well as there is the presence of potential defects. In addition to this, the correlation between actual practices and potential defects is also critically evaluated here which is represented in this part of this project report.

4.Recommendations

After the discussion on the properties of titanium and its alloys along with the challenges that get experienced during the extraction of titanium a few recommendations can be made. The failure mechanism of titanium is also discussed here from which a few recommendations are stated in order to mitigate the failure mechanisms. Hence, it is recommended to consider the operating environment and operating conditions in which the elements are going to be used for the prevention of failure mechanisms. Another way for preventing failure mechanisms is to manufacture and design the components in a specified way. Is recommended to utilize the measurement of quality control and proper testing such as non-destructive inspection, and non-destructive testing to detect potential *failure mechanisms*.

5.Conclusion

The implication of this entire project work can be described as the effective application of the tools and techniques within several processes. An effective understanding of the related terms has also been mentioned. The determination of different failures related to the extraction and another process of titanium has also been discussed. It is implicated that the application of conductive and coolant tools for cutting can effectively remove the heat from the cutting areas. This effectively improves the tool life by reducing the tool wear. The solution subjected to the challenges of titanium alloy machining relies on the selection of tools, an adjustment in the cutting parameters, applications of coolants, and environments. The Extraction, processing, and failure mechanisms of Titanium and its alloys have been discussed is discussed in this project report. In addition to that, after the completion of the project work, it can be stated that all the requirements of this project have been fulfilled.

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