

Extraction, processing, and failure mechanisms of Titanium and its alloys.

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Abstract – Works within this report have been split into two parts. Part, one explores titanium as a material, its extraction, and various processing methods that can be used. Part two explores titanium conrod failure within motorcycle engines and research reasons why they fail, and techniques that can be used to prevent them from failing again in future. Conclusions were drawn at the end of the report as to what is deemed the best methods to be used to improve the overall quality and sustainability of a grade 5 titanium conrod.

1. Part One: Titanium, Extraction, and Processing

1.1 Introduction

Titanium is the 7th most abundant metal on the earth's crust. It is used within a wide range of industries and applications globally, including aerospace, automotive/motorsport, and marine applications to name a few [1]. Extraction of the metal from the oxide in which it is naturally found is very difficult. This makes titanium an extremely expensive material (around three times more expensive than aluminium) [2].

There are many different titanium alloys, each offering varying characteristics and uses. In terms of the automotive, and specifically the motorcycle engineering industry, grade 5 titanium, or Ti 6Al-4V was found to be the most widely used alloy. Research showed that grade 5 titanium was accountable for around 50% of total titanium usage worldwide. [3]

Grade 5 titanium offers a wide range of uses and applications and boasts an impressive range of advantages. It can be heat treated to increase strength and has useful formability and is highly resistant to corrosion [3]. It is made up of 90% titanium, 6% aluminium, and 4% vanadium. As previously mentioned, grade 5 titanium can undergo further processing to manipulate its properties to become more suited to specific applications.

Grade 5 Titanium 6al-4v Properties	
Density	4.43 g/cc
Thermal Properties	
Melting Point	1604-1660°C
Solidus	1604°C
Liquidus	980°C
Mechanical Properties	
Tensile Strength Ultimate	1170 Mpa
Tensile Strength Yield	1100 Mpa
Elongation at Break	10%
Modulus of Elasticity	114 Gpa
Hardness Properties	
Brinell	334
Rockwell	C 363
Vickers	36

Table 1 – Grade 5 titanium properties [4]

As table 1 also supports, among other properties and benefits that have been mentioned earlier within this section, grade 5 titanium is used within the motorcycle industry due to it having high strength-to-weight ratio and good weldability. It can withstand high temperatures and stress, which make it perfect for use in high performance racing engines.

There are three classifications of titanium alloy. The three classifications are:

- Commercially Pure (CP) titanium alpha and near alpha titanium alloys
- Alpha-beta titanium alloys
- Beta titanium alloys

CP alpha and near alpha titanium alloys are generally non-heat treatable and weldable, offer medium strength with good creep strength and good corrosion resistance.

Alpha-beta titanium alloys are heat treatable and offer good forming properties. They also have medium to high strength whilst also offering good creep strength.

Beta titanium alloys are also heat treatable and are readily formable. They have very high strength and offer low ductility.

Grade 5 titanium is an alpha-beta alloy.

1.2 Extraction

Titanium has been abundant in the earth's crust forever, however only within the last few decades has it become easier to extract. It is still, however, difficult. Crude titanium cannot be used as it is found and therefore must be put through a time-consuming process utilizing dangerous equipment and chemicals. This process also contributes to the cost of titanium.

The name of the process used to convert crude titanium to useful titanium is the Kroll Process, named after William J. Kroll, who was the first person to invent such a process in 1940. The process follows six steps, and these steps have been documented below. [1]

1.2.1 The Kroll Process

The following table outlines each step of the Kroll Process and how crude titanium is transformed to a useable material. Information within the table was taken from titaniumprocessingcenter.com [1].

The Kroll Process	
Step One	Crude titanium is converted to a sponge through conducting an electrical charge through it. This is done in a chlorinator in which chlorine gas is then passed through the electrical charge.
Step Two	Titanium tetrachloride (created in step one) has oxygen removed which turns it to liquid form. This liquid titanium tetrachloride is then purified using fractional distillation.
Step Three	After fractional distillation, magnesium or sodium is added to the pure titanium tetrachloride which creates a metallic titanium sponge and either magnesium or sodium chloride.
Step Four	This newly formed metallic sponge is then crushed and pressed.
Step Five	The crushed and pressed titanium sponge is melted in an electrode vacuum arc furnace at very high temperatures.
Step Six	Due to each batch of titanium being very heavy, it is allowed to harden and solidify within the furnace rather than it being poured out.

Table 2 – The Kroll Process explained at each step of the process.

Due to the stages and processes that are involved in the Kroll Process, titanium becomes extremely expensive. Because titanium has such a high melting point, extremely high temperatures are required for the Kroll Process, and it is thought that conversion of metal to ingots accounts for around 30% of the cost of the entire process. Lots of energy is also needed and the entire process is very labour intensive. Due to titanium being extremely strong, the process is very slow and once finished is accountable for almost 90% of material loss [5].

1.3 Titanium Processing

Many processes can be done to grade 5 titanium to alter its properties to suit a specific application. Machining, welding, heat treatments, surface treatments, and additive manufacturing can all be applied to grade 5 titanium.

1.3.1 Titanium Machining

Machining involves the processes of turning, milling, shaping, and planning. They all work by removing unwanted material from the piece of raw material. Material is machined away using a tool that is harder than the piece being machined. Rough machining is fast but commonly leaves the surface of the material rough, and imprecise. Fine machining, however, is much more capable of achieving high accuracy and brilliant surface finish. [2]



Figure 1 – Titanium machining [6]

1.3.2 Titanium Welding

Welding involves the process of joining two pieces of material together with a molten bead of metal. Common welding types for use on grade 5 titanium are Gas Metal Arc (MIG) or Tungsten Inert-Gas (TIG) welding. There are a wide range of weld types that could be used on titanium; however, it is heavily dependent on the component being welded, and the application that it would be used for. [2]

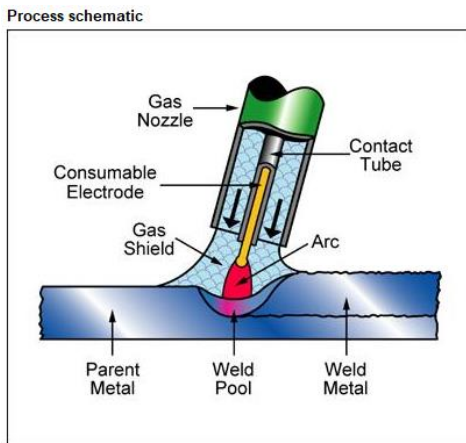


Figure 2 – MIG welding schematic [2].

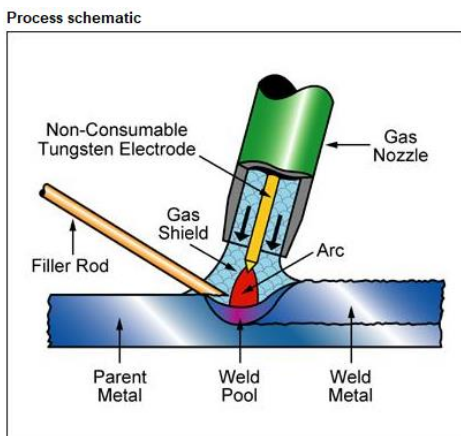


Figure 3 – TIG welding schematic [2].

Both above welding techniques are suitable for use on grade 5 titanium, it should be noted that grade 5 titanium has high reactivity with oxygen and nitrogen, and therefore requires the use of inert shielding gases during welding processes.

1.3.3 Titanium Heat Treatments

Heat treatments can be used to improve mechanical properties including strength, ductility, and toughness. Commonly, annealing is the most widely used form of heat treatment on materials.

Annealing is used to increase fracture toughness, ductility whilst the material is at room temperature, dimensional and thermal stability, and creep resistance. A vast majority of titanium components are placed into their service having already been annealed.

There are various methods of annealing which can each achieve different things, so it is vital that the correct annealing method is chosen to achieve the desired outcome for the component.

Commonly, the type of annealing that is used for alpha-beta grades of titanium is solution annealing. Solution annealing works by heating the component to temperatures of around 1000°C and holding it there for a long period of time. During this time, any interstitial elements are dissolved, and a homogenous microstructure is formed. The component is then rapidly cooled, commonly in water, which prevents the formation of coarse microstructures on the surface.

Sometimes, the component is then aged after it has been annealed. Aging is completed by heating the material to a lower temperature of around 500-550°C and then held for several hours to allow for hardening to occur. This then results in increased strength and hardness, as well as improved fatigue resistance [7].

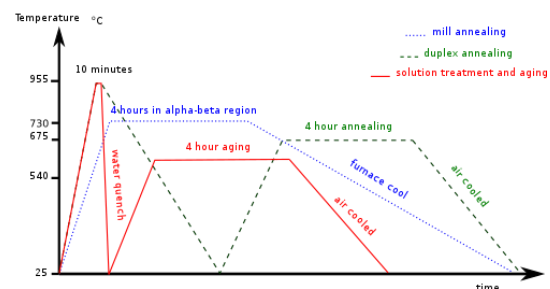


Figure 4 - Annealing process [8]

1.3.4 Titanium Surface Treatments

It is possible to use surface treatment techniques with grade 5 titanium. Some of these techniques could include chemical etching, plasma spraying, and anodizing. The use of surface treatments can be highly beneficial when aiming to improve corrosion resistance, wear resistance, and biocompatibility.

Deciding the correct surface treatment technique to use with titanium is heavily dependent on the intended use and desired outcome for the component. There are three main types of titanium surface finish that will be discussed within this section.

Plasma/ion nitriding enhances friction, wear, fatigue, and corrosion properties on the titanium components. The process works by thermochemically introducing nitrogen to the outside surface of the material. This method has been used extensively with internal engine components like crankshafts, and gearbox components [9].

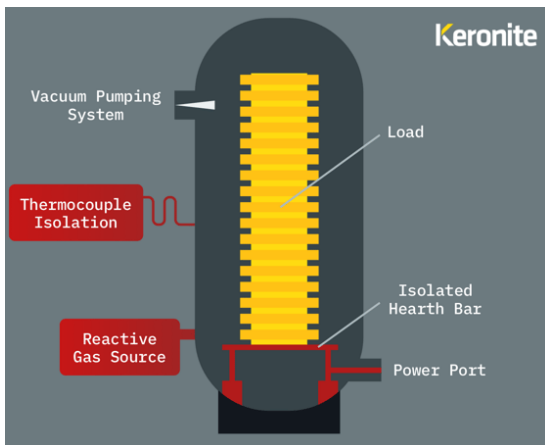


Figure 5 – Plasma nitriding process used to surface treat titanium components [9].

Plasma nitriding uses extremely high temperatures (almost 600°C), which causes an issue due to it being very expensive, and some thermal distortion could still occur with this process. Using lower temperatures can reduce this risk of thermal distortion, however they also reduce hardness of the coating.

The use of plasma nitriding on components can offer large benefits in terms of surface hardness, with hardness being measured at around 1100-2500HV for titanium components.

Titanium anodizing can also be used typically to increase component strength by introducing a thicker oxide layer on the material surface. There are many benefits to titanium anodizing, including increased friction performance, anti-galling, better resistance to water, and very little change in dimension to the original component.

The use of titanium anodizing still maintains the components' high resistance to corrosion and heat, making it a very beneficial surface treatment that can be used to enhance component performance. [9]



Figure 6 – Titanium anodizing colour chart [10]

By adjusting the oxide level that is present on the material surface, then the spectrum of light is adjusted, this then alters the perceived colour of the component, this is shown in figure 6.

Plasma Electrolytic Oxidation (PEO) is a three-stage coating process that is heavily favoured due to its comparative flexibility. They can withstand high levels of wear and are also resistant to cracking. By altering the electrolyte bath used, specific properties and characteristics can be introduced to the material [9].

2. Part Two: Titanium Connecting Rod Failure

2.1 Introduction

Titanium connecting rods, also known in industry as conrods, are used by many major motorcycle manufacturers due to their comparative strength and fatigue properties of high strength steels, but mainly because they are around 60% less dense than what a steel conrod would be [11].

Since the titanium conrods are much less dense than a steel option, this means that there are much fewer bearing loads throughout the engine, as well as lower vibration levels, which ultimately allows the engine to achieve higher power at higher rpms easier. Ultimately, a titanium conrod makes the reciprocating mass within the engine lighter, whilst also being stronger [11].



Figure 7 – Titanium connecting rods from a Ducati motorcycle [12].

As with any internal engine components, especially within a racing context, it is of course possible that component failures could occur. The following sections of this report will outline a titanium connecting rod failure from a motorcycle engine and will discuss the reasoning for why the component failed. It will also outline steps and any preventative measures that could be taken to prevent any failure from occurring again in future.

When a conrod fails, commonly it has catastrophic effects on the rest of the engine and can result in holes being punched through the crank cases.

2.2 Common Causes of Failure

There are some common causes of conrod failure, which will be discussed within this section of the report.

Common causes of conrod failure are:

- Fatigue
- Pin Failure
- Over Revving
- Hydrolock

Generally, fatigue is the most common cause of conrod failure. As the conrod goes through its working cycle, it is constantly subject to high levels of compression and expansion during the combustion process. As this happens repeatedly during power and exhaust strokes, the conrod material becomes increasingly worn out, causing it to become brittle to a point where it would eventually cause critical failure.

If an engine is being ran excessively lean, or hot, this can also accelerate wear on the conrod which could bring failure quicker. Dirty or old engine oil can also act as a catalyst to cause conrod failure quicker.

In a materials context within this report, this is the area of conrod failure that we are mainly interested in and will explore further. Brief explanation of other causes of conrod failure can be found below.

Pin failure, namely the gudgeon pins are subject to high levels of wear. These pins can snap, therefore meaning that the conrod is no longer connected to the rest of the engine. This can cause severe engine failure, causing the conrod to go through the crank case, or even bending the crankshaft. More commonly, a severe loss in power is experienced and if the engine is stopped quickly then it could be possible to salvage the engine. [13]

Over revving and hydro lock are both also causes of conrod failure. Over revving is very common in racing engines, when the engine is revved to its maximum, especially during phases where the motorcycle is coming down through its gear box. This occurs due to forces acting on a conrod increasing dramatically at high RPM's.

Hydro lock occurs when water ingresses into the piston chamber. If only a small amount of water finds its way into the chamber, then it may be repairable. However, if a large amount of water gets into the piston chamber and fills all available space, then the connecting rod will bend under these stresses or even snap [13].

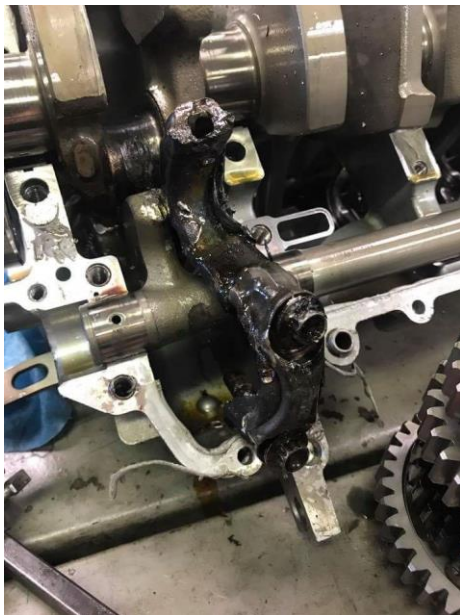


Figure 8 – Conrod failure in a 2015 Yamaha R1 motorcycle engine [14].

The following figure outlines all properties of titanium taken from Ansys Granta EduPack software which provides a general overview of the stresses and forces that a titanium conrod should be able to withstand.

Composition (summary)

Ti + alloying elements, e.g. Al, Zr, Mo, Si, Sn, Ni, Fe, V

General properties				
Density	①	4.43e3	-	4.79e3 kg/m ³
Price	①	* 19.1	-	20.9 GBP/kg
Mechanical properties				
Young's modulus	①	100	-	120 GPa
Yield strength (elastic limit)	①	470	-	1.09e3 MPa
Tensile strength	①	552	-	1.17e3 MPa
Elongation	①	6	-	20 % strain
Hardness - Vickers	①	181	-	370 HV
Fatigue strength at 10 ⁷ cycles	①	* 351	-	633 MPa
Fracture toughness	①	50	-	84.1 MPa.m ^{0.5}
Thermal properties				
Melting point	①	1.5e3	-	1.67e3 °C
Maximum service temperature	①	330	-	540 °C
Thermal conductor or insulator?	①	Poor conductor		
Thermal conductivity	①	6.1	-	12 W/m.°C
Specific heat capacity	①	509	-	583 J/kg.°C
Thermal expansion coefficient	①	8.14	-	9.8 µstrain/°C
Electrical properties				
Electrical conductor or insulator?	①	Poor conductor		
Optical properties				
Transparency	①	Opaque		
Eco properties				
Embodied energy, primary production	①	* 587	-	647 MJ/kg
CO2 footprint, primary production	①	* 33.9	-	37.4 kg/kg
Recycle	①	✓		

Figure 9 – Titanium properties taken from Ansys Granta EduPack software [2].

2.3 Potential Improvements or Mitigation Procedures

There are many prevention methods that could be taken to ensure that conrod failure does not occur again in future. Some simple methods including better quality of manufacture, and improved component design could be undertaken to improve distribution of loads evenly across the component and minimize stress concentrations that are present. It is important to consider the operating conditions of the engine, like peak rpm, power, and torque to fully understand how the component should be designed adequately.

As previously discussed within this report, heat treatment and surface treatment methods could be used to improve the overall strength of the titanium conrod, while not completely altering the dimensions of the component. Titanium, although it is a non-ferrous metal, can be case hardened. It would also be a wise suggestion to flame harden the conrod. Induction hardening would be a sensible option.

Induction flame hardening allows for the surface of the material to be hardened with minimum distortion effects or oxidation. Using this process, electricity is used to heat the surface of the

component into an austenitic phase-region, and then is rapidly cooled by a gas or a liquid jet which creates a martensitic surface layer on the component. The depth of hardening achieved is dependent on the frequency of the electromagnetic field used. Using flame hardening, heat is applied through means of one or more high temperature gas powered burners, and again is cooled rapidly.

Both processes are versatile and can be used differently to work components that cannot readily be furnace treated or case hardened in a traditional way. These methods allow for full control on hardening on desired areas of the component.

Titanium nitride coating could also be used to improve the general strength of the conrod. The use of this TiN coating would also improve the frictional properties of the conrod, whilst also including moderate resistance to oxidization. The use of such a coating would increase the sustainability of the component and ensure that it could be used for the entirety of its intended use within a high-performance motorcycle racing environment.

Typical Properties

Appearance	Bright gold metallic colour
Coating Thickness	1-4 microns
Hardness	2300 Hv
Melting Point	2800°C
Max Operating Temp	500°C
Friction Coefficient	TiN/TiN 0.08 - 0.25 (Static) TiN/TiN 0.05 - 0.15 (dynamic) TiN/HSS 0.25 - 0.35 (Static)
Elastic modulus	600 Gpa
Corrosion Resistance:	Chemically very inert, insoluble in all acids except HF. Insoluble in all alkalis. Oxidation resistance in air to 400°C
Toxicity:	used in medical prostheses, US Food & Drug Administration has no objection to the use of TiN in the food processing industry.

Figure 10 – Properties of titanium nitride coating that could be used on grade 5 titanium conrods.

2.4 Conclusion

In conclusion, the use of heat and surface treatments can greatly improve the performance and durability of grade 5 titanium conrods in motorcycle racing engines. These treatments can enhance the material properties of titanium, making it stronger and more resistant to wear, fatigue, and corrosion.

Heat treatments such as annealing, solution treatment, and aging can be used to refine the microstructure of titanium, improving its strength, ductility, and fatigue resistance. This can be particularly beneficial for conrods that experience high cyclic loads and stresses during racing. By optimizing the heat treatment process, the material properties of the titanium can be tailored to meet the specific requirements of the engine and the racing conditions.

Surface treatments such as shot peening, nitriding, and ion implantation can be used to improve the wear resistance and fatigue strength of titanium conrods. These treatments can create a compressive residual stress on the surface of the material, which can help to prevent cracks and fractures from forming. They can also improve the lubricity of the surface, reducing friction and increasing efficiency.

By combining heat and surface treatments, it is possible to create a grade 5 titanium conrod that is optimized for performance and durability in motorcycle racing engines. However, it is important to note that these treatments must be carefully controlled and applied, as any deviations can result in reduced performance or even failure of the conrod.

Some of the above-mentioned techniques have been explored in detail within this report and their benefits discussed. It is felt that with the information provided within this paper, justified decisions can be made regarding optimization of grade 5 titanium conrods which would prevent them from failing again in future.

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