Nd:YAG laser welding in Titanium-6242

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Project

Nd:YAG laser welding in Ti-6Al-2Sn-4Zr-2Mo

Summary

This report is the final result of a Bachelor of Science degree. The project has been performed in cooperation with Volvo Aero Corporation at the University of Trollhättan/Uddevalla. The core of the project has been to use an Nd:YAG laser unit and weld butt joints in the Titanium alloy Ti-6Al-2Sn-4Zr-2Mo, and investigate how the welding parameters affects the joint, as well as starting up a project routine for the laser welding equipment at HTU. The parameters that have been analysed are welding speed (Wv), Wire feeding rate (Wf) and laser effect (P). These were compared to measured results of top and root side reinforcement, top and root side width and porosity. There have also been distortion measurements performed. The distortion was visualised through surfaces generated by point clouds obtained from a CMM machine. The weld geometry data and porosity levels were analysed using Modde, which is software for planning and evaluating design of experiments. The major conclusions from the evaluation analysis were:

- The top reinforcement is increased by high wire feeding speed, and decreased by high laser power.
- The root reinforcement is increased by high values for the wire feeding speed, and decreased by higher values for the welding speed.
- The top width is affected only by welding speed. An increase in welding speed will generate a decrease in width.
- The root width is decreased by increased welding speed. An increase in width will appear when values for laser power and wire feeding rate are at high values.
- The porosity is affected by welding speed and laser effect. An increase of the latter will decrease the porosity level, whereas increased welding speed increases the level. A combination of low laser power and high welding speed will increase porosity. **Keywords:** Laser welding, Nd:YAG, Titanium, Ti-6Al-2Sn-4Zr-2Mo
Preface

This report describes the findings of a project on the subject of Laser Welding in Titanium 6Al-2Sn-4Zr-2Mo, and represents the concluding assignment of a Bachelor of Science degree in Mechanical Engineering given by the University of Trollhättan/Uddevalla.

The tests were carried out using robotic laser welding on laser cut 50x190x2.1 mm TI-6242 sheets at the University of Trollhättan/Uddevalla. This thesis was commissioned by VAC in order to investigate the effect of Nd:YAG laser welding in this specific alloy. The main objectives of the project were to: investigate the effect of changing different parameters such as wire feed, power supply and welding speed, in the specific Titanium alloy, TI-6242, and most important, to start up the Nd:YAG welding equipment at HTU for welding of Titanium.

The authors would like to thank everyone that was involved in this thesis. Peter Jonsson at VAC and everyone that is employed in the machinery hall in Trollhättan. Additionally Kjell Hurtig deserves an extra credit for his tremendous assistance.
Symbols and abbreviations

- HTU - Högskolan i Trollhättan Uddevalla (University of Trollhättan Uddevalla)
- VAC - Volvo Aero Corporation
- Nd:YAG - Yttrium Aluminium garnet, doped with Neodyme
- Titanium 6Al-2Sn-4Zr-2Mo - Titanium alloyed with 6% Aluminium, 2% Tin, 4% Zirconium and 2% Molybdenium. Also Ti 6242
- $\rho$ - Density
- $\alpha$ (alpha) phase - Hcp structured Titanium
- $\beta$ (beta) phase - Bcc structured Titanium
- Hcp structure - Hexagonal closed package. A crystal structure in materials that has the shape of a hexagon
- Bcc structure - A crystal structure in materials that has the shape of a cube.
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Introduction

This project represents the concluding assignment in a Bachelor of Science degree in Mechanical Engineering given by the university of Trollhättan/Uddevalla.

The project was planned for 10 weeks and took place mainly at HTU. Although some testing and information seeking was carried out at VAC.

This report is intended for anyone interested in laser welding and material science.

1.1 Background

Within the Aerospace industries the requirements of welds in fabricated aerospace components are extremely stringent. Welds with high quality and containing no flaws are required. At Volvo Aero Corporation (VAC), Tungsten Inert Gas welding is the most frequent used joining method for manufacturing of fabricated structural components for jet engines. The welding is mainly carried out in machines or with robots. Continuous improvements of production procedures are fundamental. In this contest the optimisation of the process, welding procedures and parameters are very important.

The distortion produced by TIG welding, due to relatively high heat input, makes the manufacturing more complicated. This is an important reason why alternative welding methods with less heat input are needed. It is known that laser welding gives high quality welds and involves less heat input than other welding methods, so that its application could be considered in order to minimise the deformation while maintaining high quality of the weld. In particular the Nd:YAG laser is a good candidate for this purpose because of the possibility to guide the beam through a fibre optic which makes the process very versatile. For certain application Nd:YAG can be considered as an alternative to TIG welding. In this work Nd:YAG laser welding of Ti6Al-2Sn-4Zr-2Mo sheet material, butt welding will be evaluated. Due to the power intensity Nd:YAG welding can be performed either as key hole or conductive welding. However this thesis will just investigate the keyhole method.

The Ti6Al-2Sn-4Zr-2Mo alloy is currently one of the alloys used for the Intermediate case (IC), a large structural casing in the front part of the aero engine. This component is predominantly made of large one-piece castings today. Work is ongoing to evaluate if there are competitive fabrication alternatives, i.e. to fabricate from small casting(sheet material/forging. A fabrication of an IC will need a lot of welding where as little distortion as possible is required to make fabrication a competitive alternative.
1.2 Purpose

- Start up at HTU with Nd:YAG laser welding in Titanium.
- With the assistance of Non-destructive testing and destructive testing investigate the effects of Nd:YAG laser welding in Ti6Al-2Sn-4Zr-2Mo.
- To investigate how the material is affected by keyhole welding and to summarise the result.

1.3 Scope

- Nd:YAG laser welding will be the method carried out.
- Butt joints in laser cut sheets will be used.
- All welding will be performed with filler material in the joint.
- Plan and evaluate the tests Design of Experiments.

1.4 Equipment

- Robot ABB IRB 4400
- Laser Rofin CW 025
- Feeding wheel attachment Esab Cw3000
- Measuring machine JohanssonP19 with ancillary software.
- Microscope
- Test preparation equipment
- Purge Chamber
2 Laser welding

Laser means "Light Amplification by Stimulated Emission of Radiation". In practice, 3 types of laser are available for welding: CO2, Nd:YAG and diode laser. This project will concentrate on Nd:YAG.

The use of robotic laser welding has additionally increased in industrial output. Today most lasers are used for welding and cutting applications. The motor car industry has been the precursor in this field however other branches of industry are starting to realise the advantages of robotic laser welding. The use of power lasers is a welding technology, which is on the verge of a definitive breakthrough. These days, lasers are as reliable as other conventional workshop machinery. The unique advantage compared to other welding methods is due to its low heat effects and high welding speed.

Most materials that can be fusion welded can also be laser welded with laser. Materials that are not appropriate for laser welding are those with high reflectance for infrared light and high thermal conductivity, such as gold, silver and copper[Ref 5].

2.1 History

The first laser was constructed in 1960, when a scientist called Theodore Maiman managed to reach a laser stadium with a ruby crystal with the help of flash-discharging lamps.

Soon after this breakthrough lasers were constructed with other medium than ruby crystals. One of the first lasers with other active materials was a laser that used calcium fluoride doped with samarium or uranium. The first gas laser came in 1961. It used a mixture of helium and neon. It was a major performance in the world of physics. However, the lasers constructed up to this point were all working in the infrared part of the spectrum. It would take yet some time to create a laser that generated a beam of visible light.

In the end of the 60’s, industrial applications had been developed, and the welding process was amongst those.

By the 1970s, laser beam welding was restricted to thin materials and low speeds due to the lack of continuous power available. The high performance data and deep penetrating abilities of CO2 and YAG lasers have promoted the development of laser beam welding in the last 20 years [Ref 6].
2.2 The principle

Laser is an energy converter and, it produces a beam of monochromatic, coherent radiation. This means that all of the radiation waves are in phase and have the same wavelength. This takes place inside of resonator, which is a medium with reflective ends. The material in the medium varies depends of what kind of laser it is. This report will focus on the ND:YAG laser, for which the wavelength is 1,06m.

The source of energy in a Nd:YAG laser is a crystal of Yttrium-Aluminium garnet (Y₃Al₅O₁₂) doped with Neodymium(Nd³⁺). Nd³⁺ replaces some of the molecules in the Yttrium-Aluminium garnet.

To obtain the energy in a YAG laser Krypton or Xenon lamps are often used as input energy. The lamps can be placed in some different geometry’s to reach its maximum efficiency. These lasers are called lamp pumped. There are also diode pumped lasers but these will not be explained in this report [Ref 4].

2.3 Geometries

2.3.1 Elliptic geometry

The first geometry has an elliptical or multi-elliptical cavity around a YAG rod, which is placed in the focus of the ellipses. The focusing surfaces of the cavity is coated with a reflective material i.e. gold, in order to increase the level of input light to the rod. This geometry is often used in pulsed lasers.

Figure 2.1 Elliptic geometry [Ref 4]
2.3.2 Slab geometry

The second geometry uses a crystal slab instead of a rod. This combined with the shape of the reflective surfaces of the cavity increases the efficiency of the excited energy. Partly because the fact that the thermal gradients are lower in a slab than in a rod and, and partly because the surface area of the cavity is greater compared to the area of the medium itself than for the elliptical geometry.

![Slab geometry](Ref4)

Figure 2.2 Slab geometry [Ref 4]

2.3.3 Helical geometry

The helical geometry uses a lamp in the shape of a helix wrapped around the medium, which in this case is a rod. Here the rod and helix lamp is enclosed in a circular cavity.

![Helical geometry](Ref4)

Figure 2.3 Helical geometry [Ref 4]

These three geometry’s are so called face pumped lasers which all are pumped by lamps. They all work accordingly to the principle: when the lamps pump light into the rod, it reflects on the ends of the rod. In one end there is a completely reflective mirror and in the other end there is a semi-reflective one. The input light will stay inside the rod and gain energy bouncing of the end mirrors until its energy level is high enough to break through the semi-reflective mirror. They are the most common constructions in industrial lasers but they are not the most efficient ones [Ref 4].
2.4 Equipment

To obtain the level of energy required to weld and cut through metal, the laser beam must be amplified. This is done with four excitation units following each other. This increases the energy to a level where it is high enough to break through the last output mirror. This generates very large amounts of heat, which makes enormous cooling sections a necessity. For lamp pumped lasers the efficiency is only 3-4%. That makes it quite obvious that cooling is very important.

When the laser beam has reached its threshold energetic state and broken through the output mirror, it has to be led to an incoupling unit. This unit leads the laser beam into an optic fibre and finally to a focusing unit in, which the beam is focused to its wanted diameter[Ref 4].

![Figure 2.4 The laser pumping unit used in this project [Picture from HTU]](image)

2.5 Focusing units

The focusing units are available in some different models. There are both so-called single focus and double focus units available. The single focus optics collects the laser beam from the fibre and makes it parallel with a collimator lens. Then the focusing lens focuses the beam to its requested focal length.
The double focusing unit uses the same principle, but it has an extra lens that divides the beam in two. Depending of what kind of process the laser shall perform, the two beams can have its focal points either separated or displaced in altitude. The possibility to use double focus makes it possible to adapt the laser to a variety of welds. The penetration depths can be increased, the gap in a butt weld can be wider and one beam can be used as a preheater[Ref 4].

Figure 2.6 The principal of double focus (twin spot) [Ref 4]
2.6 **Filler materials**

It is possible to weld without any filler material when laser is used. The high energy density melts the material in the focal point. However, filler materials increases the number of applications and, the material used depends on what material the work piece is made of. Filler metal is used occasionally in laser welding especially if there is a gap to be filled between the pieces. Another reason can be to achieve requirements of the weld geometry[Ref 4].

2.7 **Shielding gases**

Since a laser beam can travel through the atmosphere without any noticeable distortion, welding is done in air. This makes it vulnerable to oxidation in the melt pool. Oxidation can cause pores, which considerably reduces the quality of the weld. That is why an inert gas often is used. The gas itself doesn’t distort the beam and, this makes it possible to let the gas flow from the same nozzle that generates the laser beam. The gas also keeps the plasma cloud generated in the pool away from the beam. This cloud has an absorbing effect on the laser, which reduces the power density in the focal point. Since YAG laser welding often is used for penetrating welding, gas shielding must be done on the root side of the weld too. This is done by using fixtures that has a gas flow within itself. Gases that are commonly used are helium, argon and hydrogen or mixtures of these. Argon is the most preferable one due to its lower price compare to helium. Hydrogen is never used in its pure form but, it is used as a mixture to the inert gases (Hydrogen is not an inert gas)[Ref 4].

2.8 **Personal handling**

Potential dangers and security aspects when handling a laser-welding unit are a bit different from other welding units. There are a variety of international standards on how to behave in the presence of any kind of laser device. It is recommended that the operator is educated in the fundamentals of optics and physics to better understand the hazards involved.

2.8.1 **Electrocution**

For any electric equipment used in industrial applications, precautions must be taken. Voltages and currents can be at well above lethal levels. All switches must be turned of and locked before any work on the equipment is performed.
2.8.2 Skin hazards
Severe burns appear immediately with any contact with the main beam.

2.8.3 Chemical hazards
Fumes from the melting pool could be poisonous. Here the hazards are the same as any kind of welding process. Good ventilation is important.

2.8.4 Eye hazards
A laser beam has an incredible reach. That makes it absolutely vital that any kind of laser welding unit is shielded from curious eyes. Even reflected beams are dangerous. When using a Nd:YAG laser it is important to use a protective filter on any kind of viewing window. If an operator has to work in an area where it is impossible too completely shield the beam from the operators’ line of sight, protective goggles must be worn at all times. Goggles are available with protective filters for wavelengths that practically any laser is radiating[Ref 4].

2.9 Keyhole and conductive welding
There are two different approaches to laser welding, keyhole and conductive welding. When the laser intensity is above a threshold the surface melts. Liquid metals absorb much more light than solid ones, so the heat input suddenly increases. This raises the metal's temperature above the boiling point, generating metal vapour. The pressure of this vapour opens a channel around the laser beam, forming what is called a keyhole. The formation of a keyhole is of fundamental importance for penetration welding.
When the laser has low intensity conductive welding occurs. The energy is transported by conduction of heat and melts the material. Using this method shallow and wide welds are to be expected. Generally it can be said that switching from keyhole to conductive just reduce the power supply and weld speed. Down below there are two figures illustrating the cross sections of these welds [Ref 6].
3 Titanium

3.1 Why titanium in aerospace engines?

High strength/density ratio, \( \rho = 60 \% \) of steel. This is very important since low weight is of great importance in aerospace applications, low weight leads to lower fuel consumption, thus the flight time and range are improved. The most common alloy within the aerospace industry is Ti 6Al-4V. Maximum working temperature is around 400°C. For the alloy Ti 6Al-2Sn-4Zr-2Mo, the maximum temperature is around 450°C.

3.2 Laser welding in Titanium

Titanium and its alloys exhibit five major chemical and metallurgical characteristics, which influence welding operations.

- Sensitivity to embrittlement when contaminated by small parts of oxygen, carbon, nitrogen and hydrogen.
- Reactivity when heated up to welding temperatures. Sensitivity to embrittlement as a function of alloy content when subjected to thermal cycles involved in most welding operations.
- Sensitivity to embrittlement when highly alloyed with metallic elements.
- Susceptibility to stress corrosion[Ref7].

The most important precaution in welding titanium is to avoid contamination with carbon, oxygen, hydrogen and nitrogen. These elements form interstitial-type solid solutions with titanium. They sometimes remain as residuals from different processes or are added intentionally for strengthening purposes. If present in sufficient quantities ductility and toughness are seriously impaired. Interstitial components can not completely be avoided in welded joints. However, using proper cleaning, welding procedures and filler materials can control them. Filler metals with low interstitials are often used to improve weld ductility[Ref 7]. More can be read about Titanium in Appendix C
3.2.1 Alloy selection

There are different types and forms of titanium and its alloys. This also means that there are different properties from each one of them. Every single alloy is specific in some certain way.

3.2.1.1 Alpha alloys

Alpha alloys are readily adaptable to all kind of types of welding. The alpha alloys are just slightly affected by the heat treatment and microstructural variations followed by the welding operation. Welded joints in alpha alloys are ductile, and their strengths equal or exceed the properties of the base material.

3.2.1.2 Alpha-beta alloys

Weldability of these alloys varies with alloy content and weld applications. Weld ductility decreases as beta stabilising alloy contents are increased. Embrittlement is observed in these alloys when beta stabilisers reach over 3% (5% if vanadium is used). Using these guidelines, alloys that contain 3-4% of less potent beta stabilisers, adaptability in most welding applications are obtained.

3.2.1.3 Beta alloys

These alloys are promising for welding applications. When used as welded joints in commercial alloys they are quite ductile. However, when the joints are heat treated to obtain maximum strength, ductility is severely reduced. Therefore further research in this matter is to be expected[Ref 7].
4 Experimental

4.1 Equipment description

The test was carried out using an IRB 4400 robot, Rofin CW 025 laser unit and a wire feeder manufactured by ESAB model CW 3000. Fixture was supplied by VAC. This fixture was chosen because a comparison between the distortion of keyhole and conductive welding was to be made. However conductive welding was excluded due to time consumptive construction work with the equipment.

Due to oxidation of the sheets a purge chamber was constructed. The fixture was tightened to the floor of the chamber, and the gas flow was led in the chamber from three different locations. One at the back, one at the front and one in the middle. The middle gas flow was led through a pipe with small holes and was acting as a root gas protection. Purging was done three minutes before each welding process in order to achieve complete fullness of Argon in the chamber. As figure 4.2 shows the sheets were constricted in one end and the welding was carried out in the left direction.
Initially air was used in the cross jet which also contributed to the oxidation in the welds due to depression of air. The cross jet is a protective high pressure air curtain that protects the shielding lens from soot. Trials without using the cross jet was also performed but then black soot was gathered at the lens, which reduced the penetration quite significantly. This has been analysed at VAC and is a mixture of Titanium and Aluminium (TiAl), probably Ti₃Al. This is believed to occur due to the high energy density of the laser beam. This phenomenon was eliminated by using Argon supplying the cross jet as well.

![Fig 4.3 Dust gathered on the shielding lens. [Picture from HTU]](image)

In order to be sure that the right filler speed was used, a manual calibration had to be performed. Under a short period of time, filler wire was fed, and then measured. While this was being done, the voltage over the feeder motor was measured, and this voltage was used as reference. This procedure was repeated several times, and made it possible to adjust the wire feeder to the desired rate with good accuracy.

### 4.2 Testplan

A test plan containing one high and one low value for every parameter was developed according to Design of Experiments. Design of experiments is a method for planning, performing and evaluating, where all parameters included can be varied according to a predetermined schedule. In order to control the linearity of these parameters a midpoint is also included in the trials. The parameter factors that were to be evaluated were wire feeding rate, laser effect and welding speed. The trials, once the limiting values had been set, were given a run number. These run numbers were randomly placed in the running order chart seen in table 5.1. The length of every joint was 90mm.
Table 4.1. Running order

<table>
<thead>
<tr>
<th>Run Nr</th>
<th>Wf(mm/m)</th>
<th>P(kW)</th>
<th>Wv(mm/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000</td>
<td>1.6</td>
<td>1200</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
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<td>480</td>
</tr>
<tr>
<td>3</td>
<td>500</td>
<td>1.6</td>
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</tr>
<tr>
<td>4</td>
<td>1250</td>
<td>2.05</td>
<td>840</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>2.5</td>
<td>480</td>
</tr>
<tr>
<td>6</td>
<td>1250</td>
<td>2.05</td>
<td>840</td>
</tr>
<tr>
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<tr>
<td>11</td>
<td>1250</td>
<td>2.05</td>
<td>840</td>
</tr>
</tbody>
</table>

Some parameters have throughout the trials been kept constant. The focus of the laser beam was in every weld kept at the surface of the sheets, the focal length was constant at 200mm, and the gas flow was kept constant at around 50 litres per minute to assure proper shielding from air.

5 Results

5.1 Joint appearance

The joints were in the first stage visually inspected in order to determine the level of oxidation, and to gain an impression of the general appearance. One of the joints (joint 1) is displayed in the following section, the rest are presented in Appendix A.
Joint 1

- Good appearance
- Little or no oxidation

Figure 5.1 Joint 1 [Picture from HTU]

For images of all welds see Appendix A, and for cross sections see section 5.3.2

In general, the welds had a good appearance with little oxidation. All except welds 5 and 8. Those were subject to massive overheating with a burn-trough as a result. The oxidation seen in some of the welds is a result of flaws in the purge chamber construction. The plastic tightening attached to the robot arm and top of the purge chamber had to be adjusted after a few runs, or else it started to leak.

5.2 Distortion

The distortion was evaluated by measuring each sheet in a coordinate measuring machine. The sheets were centred in a fixture manufactured at HTU. The machine used was a Johansson P 19. On each sheet 2500 measuring points were obtained. Figure 5.8 displays the measuring probe in action.
5.2.1 Visualisation of distortion

Each sheet generated a point cloud converted by Unigraphics into a JPEG file. The surface generated by the point cloud is compared to a plane and the deformation is shown in the figure for each sheet. See figure 5.9. The scale is shown to the right. The sheets are all constricted on the lower short end side. The rest of the sheets can be viewed in Appendix B.
Sheet 1

The scale to the right shows that the maximum deviation is –0.4111mm. It has been measured in relation to a horizontal plane, and is located at the upper short side. The maximum deviation in positive direction is 0.1974mm, located in the centre of the left long side. What this tells us is that sheet has obtained the shape of an arch, with a slight twist.

5.2.2 Conclusions

The most significant parameter affecting the deformation of the sheets seems to be welding speed, since the sheets that are most deformed has been welded with the lower velocity value.
5.3 Joint geometry

5.3.1 Test preparations

The test preparation was done at VAC material laboratory. First each joint and sheet was cut in two different sections. The first cut were placed 20 mm from the welding start point, this cut represents the A section. The next cut were placed additionally 15 mm from the A section and represents the B section. The sections were then moulded into bakelite and polished. Finally the samples were etched in Kroll and then examined under a microscope.

5.3.2 Evaluation

The main objective with the microscope analysis was to evaluate the geometry of the joint. Figure 6.1 shows a typical keyhole weld and some distances. Note that there is no appreciable difference between C1 and C2 so the letter C denotes them both. The joints have also been inspected for porosity (P), which have been graduated from 1-4, where 1 is the least, hence the most favourable. The geometries for each joint can be viewed below

![Keyhole weld model](Ref4)

Figure 5.10 Keyhole weld model [Ref4]
<table>
<thead>
<tr>
<th>Joint 1A(25X)</th>
<th>Values(mm)</th>
<th>Joint 1B(25X)</th>
<th>Values(mm)</th>
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<tbody>
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<td>MO3-1090</td>
<td></td>
<td>MO3-1090</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• por=4</td>
<td>• por=4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Bh=0.39</td>
<td>• Bh=0.41</td>
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<td></td>
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<td>• Ch=0.22</td>
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<td>• B=2.40</td>
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<td></td>
<td>• S=0.64</td>
<td>• S=0.71</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Joint 2 A(12.5X)</th>
<th>Values(mm)</th>
<th>Joint 2 B(12.5X)</th>
<th>Values(mm)</th>
</tr>
</thead>
<tbody>
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<td>MO3-1091</td>
<td></td>
<td>MO3-1091</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• por=2</td>
<td>• por=2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Bh=0.49</td>
<td>• Bh=0.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Ch=0.34</td>
<td>• Ch=0.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• B=4.10</td>
<td>• B=4.21</td>
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<tr>
<td></td>
<td>• C3=3.42</td>
<td>• C=3.38</td>
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<th>Values(mm)</th>
<th>Joint 3 B(12.5X)</th>
<th>Values(mm)</th>
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<tbody>
<tr>
<td>MO3-1092</td>
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</table>
Figure 5.11 Weld 1, 2, 3. All plates have thickness 2.1 mm

<table>
<thead>
<tr>
<th>Joint 4 A (16X)</th>
<th>Values (mm)</th>
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<tr>
<td>MO3-1093</td>
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<td>MO3-1093</td>
<td></td>
</tr>
<tr>
<td>por=1</td>
<td></td>
<td>por=1</td>
<td></td>
</tr>
<tr>
<td>Bh=0.27</td>
<td></td>
<td>Bh=0.26</td>
<td></td>
</tr>
<tr>
<td>Ch=0.25</td>
<td></td>
<td>Ch=0.27</td>
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</tr>
<tr>
<td>B=3.54</td>
<td></td>
<td>B=3.49</td>
<td></td>
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<td>C=3.08</td>
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<td>MO3-1094</td>
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<tr>
<td>por=2</td>
<td></td>
<td>por=2</td>
<td></td>
</tr>
<tr>
<td>Bh=0.22</td>
<td></td>
<td>Bh=0.24</td>
<td></td>
</tr>
<tr>
<td>Ch=0.17</td>
<td></td>
<td>Ch=0.20</td>
<td></td>
</tr>
<tr>
<td>B=2.89</td>
<td></td>
<td>B=3.12</td>
<td></td>
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<tr>
<td>C=3.13</td>
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Nd:YAG laser welding in Ti-6Al-2Sn-4Zr-2Mo

Fig 5.12 Weld 4, 6, 7. All plates have thickness 2.1 mm.

<table>
<thead>
<tr>
<th>Joint 9A(20X) MO3-1096</th>
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<tr>
<td></td>
<td>por=3</td>
<td></td>
<td>por=3</td>
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<tr>
<td></td>
<td>Bh=0.28</td>
<td></td>
<td>Bh=0.24</td>
</tr>
<tr>
<td></td>
<td>Ch=0.22</td>
<td></td>
<td>Ch=0.17</td>
</tr>
<tr>
<td></td>
<td>B=3.23</td>
<td></td>
<td>B=2.78</td>
</tr>
<tr>
<td></td>
<td>C=3.05</td>
<td></td>
<td>C=3.10</td>
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</table>

<table>
<thead>
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<th>Joint 10A(20X) MO3-1097</th>
<th>Values (mm)</th>
<th>Joint 10B(20X) MO3-1097</th>
<th>Values (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>por=4</td>
<td></td>
<td>por=4</td>
</tr>
<tr>
<td></td>
<td>Bh=0.21</td>
<td></td>
<td>Bh=0.19</td>
</tr>
<tr>
<td></td>
<td>Ch=0.14</td>
<td></td>
<td>Ch=0.15</td>
</tr>
<tr>
<td></td>
<td>B=1.86</td>
<td></td>
<td>B=1.99</td>
</tr>
<tr>
<td></td>
<td>C=1.13</td>
<td></td>
<td>C=1.25</td>
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<td></td>
<td>S=0.79</td>
<td></td>
<td>S=0.84</td>
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<table>
<thead>
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<th>Joint 11A(16X)</th>
<th>Values (mm)</th>
<th>Joint 11B(16X)</th>
<th>Values (mm)</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td></td>
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</tbody>
</table>

24
Figure 5.13 Weld 9, 10, 11. All weld have the thickness 2.1 mm.

As can be seen in the preceding figures, the geometries of the welds differ when compared. The welds that have the most specific keyhole appearance, where a waist can be seen (see model in figure 5.10) are welds one and ten. They are both welds performed with high welding speed and low laser power. The welds with the largest width are welds two and three. They are performed with low welding speed. For a complete list of parameter settings, see table 4.1. For a list of parameter settings and responses, see table 6.1.

When viewing these images, take under consideration that the magnification varies from image to image. This is done in order to illustrate every weld as good as possible.

6 Results

The statistical evaluations of the data obtained in this project, were analysed using the Modde software for design of experiments[Ref]. The software presents a graphical interface. All the results from the runs were in the software analysed in relation to the three varying parameters, and relations between responses and parameter factors established. The design of experiments matrix containing parameter settings and responses can be viewed in table 6.1 below.

<table>
<thead>
<tr>
<th>Run order</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
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<tr>
<td>Incl/Excl</td>
<td>Incl</td>
<td>Incl</td>
<td>Incl</td>
<td>Incl</td>
<td>Excl</td>
<td>Incl</td>
<td>Incl</td>
<td>Incl</td>
<td>Incl</td>
<td>Incl</td>
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<tr>
<td>Power</td>
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<td>1.6</td>
<td>1.6</td>
<td>2.05</td>
<td>2.05</td>
<td>2.05</td>
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<td>840</td>
<td>1200</td>
<td>480</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
<td>840</td>
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<tr>
<td>Reinforcement Top(A)</td>
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<td>0.49</td>
<td>0.12</td>
<td>0.27</td>
<td>0.22</td>
<td>0.28</td>
<td>0.13</td>
<td>0.21</td>
<td>0.19</td>
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<tr>
<td>Reinforcement Top(B)</td>
<td>0.41</td>
<td>0.53</td>
<td>0.14</td>
<td>0.26</td>
<td>0.24</td>
<td>0.24</td>
<td>0.11</td>
<td>0.19</td>
<td>0.24</td>
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<tr>
<td>Reinforcement Root(A)</td>
<td>0.23</td>
<td>0.34</td>
<td>0.1</td>
<td>0.25</td>
<td>0.17</td>
<td>0.22</td>
<td>0.08</td>
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<tr>
<td>Reinforcement Root(B)</td>
<td>0.22</td>
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<td>0.13</td>
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<td>0.17</td>
<td>0.09</td>
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<tr>
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<td>Width Top(B)</td>
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<td>2.78</td>
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<td>3.3</td>
<td>3.05</td>
<td>1.53</td>
<td>1.13</td>
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<td>Width Root(B)</td>
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<td>3.19</td>
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<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>4</td>
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<td></td>
<td></td>
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</tbody>
</table>

Table 6.1 Experimental test matrix with corresponding results.
The Incl/Excl column explains whether the run has been included or excluded from the statistical analyses. As can be seen in the matrix, passes five, eight and 11 are excluded. Five and eight due to massive overheating, which made the joint impossible to measure and analyse. Joint 11 is a midpoint in the parameter setting table, and is excluded because its responses differ too much from the other welds with the same settings. More about this in section 6.6. Filler speed and welding speed is in mm/min, and power is in kW. The measured responses are in mm. Porosity is a judged scale from one to five, where one has the most pores and five is the most preferable.

### 6.1 Reinforcement top (Bh)

![Figure 6.1 Degree of explanation (R^2) and predictability (Q^2) of top reinforcement](image)

The green (bright) rectangle shows the degree of explanation of the model (R^2) which describes the percentage of the variation of the response explained by the model. The blue (dark) rectangle describes the predictive power of the model (Q^2). To determine if the degree of explanation of a model is good, a threshold value of 0.75 is often used.
The model for the top reinforcement shows good degree of explanation (R²), the scale to the left indicates that a value of 85% was obtained. The predictability (Q²) is fairly good, approximately 55%. In order to determine whether a parameter is significant or not, a 95% confidence limit was used.

![Most important parameters for top reinforcement. Wf is wire feeding rate and P is laser power.](chart.png)

The model also shows that the most significant parameter at a 95% confidence limit for top reinforcement is wire-feeding rate (Wf), which has a positive correlation i.e. increased wire feeding increases the reinforcement as expected. The effect from the laser power (P) is not significant, since the confidence interval contains zero, but cannot be excluded.
The contour plot of this model shows that with a low laser power in combination with a high filler speed, an increased reinforcement will be obtained, and that the reinforcement can be controlled within the range 0.12-0.38 mm within the selected parameter window.

### 6.2 Reinforcement root (Ch)
Figure 6.4 Degree of explanation \( (R^2) \) and predictability \( (Q^2) \) of the root reinforcement

The green (bright) rectangle shows the degree of explanation of the model \( (R^2) \) which describes the percentage of the variation of the response explained by the model. The blue (dark) rectangle describes the predictive power of the model \( (Q^2) \).

The model for the root reinforcement shows good degree of explanation \( (R^2) \), the scale to the left indicates that a value of 70% was obtained, and fairly good predictability \( (Q^2) \), approximately 50%.

Figure 6.5 Most important parameters for the root reinforcement. \( W_f \) is filler speed and \( W_v \) is welding speed.

The model shows that the filler speed is the most significant parameter. Welding speed is insignificant, because the confidence interval contains zero, but cannot be excluded because then the accuracy of the model will decrease.
Figure 6.6 Contour plot for the root reinforcement. Power is in kW and filler speed is in mm/min.

The contour plot shows that high filler speed in combination with low power generates the largest root reinforcement, and that the root reinforcement can be controlled within the range 0.08-0.3 mm within the selected parameter window.

6.3 Width B
Figure 6.7 Degree of explanation ($R^2$) and predictability ($Q^2$) for the B-width. The green (bright) rectangle shows the degree of explanation of the model ($R^2$) which describes the percentage of the variation of the response explained by the model. The blue (dark) rectangle describes the predictive power of the model ($Q^2$).

The model for the B-width shows a fairly good degree of explanation ($R^2$), the scale to the left indicates that a value of 60% was obtained, but fairly low predictability ($Q^2$), approximately 35%.

Figure 6.8 Significant parameters for the B-width.

The only significant parameter for the width is the welding speed. It has a negative correlation on the response, which means that increased welding speed decreases the width as expected.

A contour plot is not meaningful in this case, since there is only one significant parameter.

6.4 Width C
The green rectangle shows the fitting of the model ($R^2$) which describes the percentage of the variation of the response explained by the model. The blue rectangle describes the predictive power of the model ($Q^2$).

The model for the C-width shows a good degree of explanation ($R^2$), the scale to the left indicates that a value of almost 100% was obtained, and fairly good predictability ($Q^2$), approximately 60%.

Figure 6.10 Most important parameters for the C-width. Wv is welding speed, P is laser power, WfP is an interaction between filler speed and laser power, and Wf is filler speed.
The model shows that welding speed and power are statistically significant, whereas the welding speed has a negative effect on the response. Wire feeding rate and the interaction between this factor and power is also significant, but not to the same extent. These factors do however exert an increasing effect on the width.

![Contour plot for the C-width. Power is in kW and filler speed is in mm/min.](image)

The contour plot shows that a combination with high power and high filler speed generates the largest root width.
6.5 Porosity

Figure 6.11 Degree of explanation ($R^2$) and predictability ($Q^2$) for the porosity.

The green rectangle shows the degree of explanation of the model ($R^2$), which describes the percentage of the variation of the response explained by the model. The blue rectangle describes the predictive power of the model ($Q^2$).

The model for the porosity shows a good degree of explanation ($R^2$), the scale to the left indicates that a value of 80% was obtained, and fairly good predictability ($Q^2$), approximately 60%.
Nd:YAG laser welding in Ti-6Al-2Sn-4Zr-2Mo

Figure 6.12 Most important parameters for the porosity. Wv is welding speed and P is laser power.

The model shows that an increase in welding speed increases the amount of pores, and the power stands in an opposite relation. These are the significant factors for porosity.

Figure 6.13 Contour plot for the porosity. Power is in kW and welding speed is in mm/min.

The contour plot shows that high welding speed in combination with low power generates the largest amount of pores, within the evaluated parameter window.
6.6 Compilation

In order to fully appreciate the responses from the different parameters in this work, one should in the table in fig6.1 notice that trials 5, 8 and 11 have the notation excl. This means that they are not included in the Modde software analysis. Trials 5 and 8 are excluded due to massive burn-through in the joints, and could not be counted as representative in the analysis. Trial eleven is a midpoint in the test point cube, but its resulting values differ some from the two other redundant midpoints. The result will be that the uncertainty of the models created by Modde will increase. Another factor to consider is that only the results from the A-section in the joints have been analysed in the software. (see table6.1 for a complete table of results.)

7 Conclusions

7.1 Responses

The screening process performed in this project had the aim of finding out how different parameters affected different aspects of a laser-welded joint. What has been revealed here is:

- The top reinforcement is increased by high values for wire feeding, and decreased by higher values for laser effect. Thus, a combination of low effect and high feeding rate gives a higher reinforcement.

- The root reinforcement is increased by high values for the wire feeding, and decreased by higher values for the welding speed. A combination of low effect and high wire feeding rate will generate a higher reinforcement.

- The top width is affected only by welding speed. An increase in welding speed will generate a decrease in width.

- The root width is decreased by increased welding speed. An increase in width will appear when values for laser power and wire feeding rate are at high values. For this response, a combination of high power and a high wire feeding rate will generate a larger width.

- The porosity is affected by increased welding speed and laser effect. An increase of the latter will decrease the porosity level, whereas increased welding speed increases the level. A combination of low laser power and high welding speed will increase porosity.
7.2 The project
As previously mentioned, the top priority of the purposes in this project was to obtain a start-up for projects with the equipment. This has in deed been achieved. All the pitfalls that have been stepped in have been educating experiences. The authors as well as employees at HTU have gained valuable experiences on what should be avoided in order to perform trials. With these experiences as a starting point, future projects should run smoothly, and a continued and evolved cooperation with VAC is promoted.

7.3 Discussion
The trials performed in this project have been subject to a number of disturbances. To begin with there was the oxidation issue. Major efforts was put into work in order protect the welds from air contamination. The final construction of the purging chamber was functional, but had to be adjusted after only a few runs. This is what caused the oxidation in some of the welds. No equipment for oxygen measuring was used before welding. The oxygen level must be kept at a absolute minimum, thus measuring is a good idea.

The uncertainty of the Modde analyses is quite large because of the excluded welds 5, 8 and 11. The most probable reason for the overheating in weld 5 and 8 is that the shielding lens was covered with the black TiAl soot while the search for parameter settings were performed. This soot had a refractive effect on the laser beam, causing it to lose focus and energy density.

The sheets used in the trials were surface treated with Kroll solution. This is a combination of nitric and fluoride acids. They were kept in air proof bags ang treated with cotton gloves. The filler wire however, were wounded on a spool, and was never shielded from air, nor treated in any special way. In aerospace applications, the wire should always be surface treated in the same way as the work pieces. Perhaps the results would have been different if there were guaranties that the wire was clean.

7.4 Future work
This work has had the objective of a screening process to find which parameters that affect certain responses. The next level in this line of work is to locate the window in which the joints have preferable properties, and repeat the trials with a narrower window. This in order to be able to optimise the parameters to gain the type of weldings that fits determined specifications. The accuracy of the analysis models in this thesis could have been better if all the joints had been representative and included in the Modde analysis. It is not recommended to proceed in optimisation using the results without first obtaining these data.
8 References

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   ISRN:LTU-EX—00/25—SE

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Appendix A

Joint 2

- Good appearance
- Oxidation in the initial phase

Joint 3

- Good appearance
- No oxidation
Nd:YAG laser welding in Ti-6Al-2Sn-4Zr-2Mo

Joint 4

- Good appearance
- No oxidation

Joint 5 and 8

- Bad appearance due to massive overheating.
- No oxidation
Nd:YAG laser welding in Ti-6Al-2Sn-4Zr-2Mo

Joint 9

- Good appearance
- Little oxidation

Joint 11

- Good appearance
- No oxides
Appendix B

Sheet 2

Sheet 3
Nd:YAG laser welding in Ti-6Al-2Sn-4Zr-2Mo

Sheet 6

Sheet 7
Nd:YAG laser welding in Ti-6Al-2Sn-4Zr-2Mo
Appendix C

Titanium

History

The element Titanium(Ti) has a relatively short production history. Its utilisation started in the 1950’s. The element as such was first discovered 1790 in England by William Gregor. Gregor presented an analysis of a black magnetic sand that roughly corresponded to the mineral Ilmenite(FeTiO$_3$). This is one of the minerals in which Titanium occurs in nature.

In 1795, M.H Klaproth showed some similarities between Gregor’s and his own investigations, in which he had examined the oxide extracted from the mineral Rutile(TiO$_2$). The material could then be defined, and was by Klaproth given the name Titanium[Ref 1].

The early stages of attempts to separate pure Ti from its ore compounds, gave rise to nitrides, oxides and cyan nitrides. These are compounds with a metallic lustre, which often led to confusion, and a misinterpretation that they were metals.

In 1887, L.F Nilson and O Petersen accomplished 97, 4% pure Ti through the process of reducing Titanium tetra chloride with Sodium in an air-proof cylinder. Pure Ti, free from impurities was successfully manufactured in 1906.

Manufacturing and utilisation

The large-scale production of today, can be traced back to the work of W.J Kroll and M.A Hunter. The Hunter method was developed in 1906 at General electric’s, and the Kroll method was developed in 1938[Ref 1].

Titanium is the ninth most abundant element, making up about 0.6% of the Earth's crust. It occurs in nature only in chemical combination, usually with oxygen and iron.

Mineral sources for titanium are rutile, ilmenite, and leucoxene, an alteration product of ilmenite. Rutile is 93% to 96% titanium oxide (TiO$_2$), ilmenite may contain between 44% and 70% TiO$_2$, and leucoxene concentrates may contain up to 90% TiO$_2$. Only about 5% of the world's annual production of titanium minerals goes to make titanium metal. The other 95% of such production is used primarily to make white TiO$_2$ pigment. Because of its whiteness, high refractive index, and resulting light-scattering ability, TiO$_2$ is the predominant white pigment for paints, paper, plastics, rubber, and various other materials.

When Titanium is to be manufactured in large scale, the ore used is almost exclusively Rutile. The reason for this is that it has the highest content of TiO$_2$. See table1.
Nd:YAG laser welding in Ti-6Al-2Sn-4Zr-2Mo

<table>
<thead>
<tr>
<th>Material</th>
<th>TiO$_2$ Content,%</th>
</tr>
</thead>
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<td>Rutile</td>
<td>97,0-98,5</td>
</tr>
<tr>
<td>Ilmenite (from Quilon)</td>
<td>57.3-61</td>
</tr>
<tr>
<td>Ilmenite (from Florida)</td>
<td>58.0-63,0</td>
</tr>
<tr>
<td>Ilmenite (from MacIntyre)</td>
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<td>Ilmenite (from Baie-St.Paul)</td>
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</tr>
<tr>
<td>Perovskite</td>
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<td>Sorel slag (Ilmenite from Quebec)</td>
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<td>Osaka slag (Ilmenite from Japan)</td>
<td>90,0-92,0</td>
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</tbody>
</table>

Table 1 Typical TiO$_2$ content of Titanium Minerals and slags [Ref 1]

When the technique to produce Ti was refined, and its properties were made obvious, its advantages promoted further development of the material. It was shown that Ti had a positive density-strength ratio, good corrosion resistance and good properties for medical applications. The two most frequent methods for manufacturing pure Ti are the Kroll and Hunter methods. They both derive from the usage of Titanium tetra chloride (TiCl$_4$). This chemical compound is obtained when the Rutile reacts with Cl$_2$. This reaction is defined as:

$$\text{TiO}_2 + 2\text{Cl}_2 \rightarrow \text{TiCl}_4 + \text{CO}_2 + \text{Heat}$$

Or

$$\text{TiO}_2 + 2\text{Cl}_2 \rightarrow \text{TiCl}_4 + 2\text{CO} + \text{Heat}$$

Then the TiCl$_4$ must be separated in order to extract the Ti.

- The Hunter method:

  $$\text{TiCl}_4 + 4\text{Na} \rightarrow 4\text{NaCl} + \text{Ti}$$

  This is also called the Sodium Reduction Process

- The Kroll method:

  $$\text{TiCl}_4 + 2\text{Mg} \rightarrow 2\text{MgCl}_2 + \text{Ti}$$

  This is also called the Magnesium reduction process.
These may seem like obvious and easy reactions. One should keep in mind however, that Titanium is an extremely reactive metal, and there are a number of simultaneous and competitive reactions taking place during the reduction.

**The material**

The element Titanium has an atomic mass of 47, 90 amu (atomic mass unit), and 22 electrons. It has a big nucleus in which the mass is concentrated. The natural structure of its atoms at room temperature is the hcp-structure. This is known as the alpha-phase. The hcp-structure occurs in pure Ti up to 885°C where it turns in to a bcc-structure known as the beta phase. This is called the beta-transus temperature. [Ref 3]

When alloying Ti, a distinguished border is drawn between interstitial alloys and substitutional alloys. The Interstitial alloy occurs when the alloying elements are small in comparison to the host atoms. The deviation in atom diameter must be >60%. This applies for Oxygen, Hydrogen, Nitrogen and Carbon. If the atom diameter of the solvent is more similar to Ti, substitution alloys are possible. The deviation in this case must be <15%. The elements must also have the same crystal structures and equivalent chemical characteristics. To view the solubility of different elements, see figure1

![Figure 1. Atomic diameters of elements and their solute properties in Titanium](Ref 3)
There are a variety of phases for titanium and its alloys, and they will be discussed later. In addition to all the different phases, there are also some intermetallic compounds that occur in different alloying systems. Some are wanted and some are not.

**Binary systems**

A binary alloying system is a system where two similar metals have complete solid solubility. This is an isomorphous system in which uniform, homogenous crystals are formed through diffusion if, the process is given the sufficient time frames needed at the critical temperatures. See figure 2.

![Binary alloy phase diagram](image)

**Figure 2.** A binary alloy phase diagram of metals A and B, which have complete solid solubility in each other [Ref 2]

Examples of elements that under equilibrium conditions form binary systems with Titanium are:

- Hafnium
- Molybdenum
- Niobium
- Tantalum
- Vanadium
If the system is not cooled under equilibrium conditions, a cored structure forms. This structure often exhibits a lower strength in the center and lower ductility in the grain boundaries. These cored structures are often unwanted, but can be eliminated through heat treatment.

**Partially soluble alloys**

It is more common in Ti alloying systems that the solvent is not completely soluble in the solute. These systems are also binary, but they show a somewhat different behavior.

Depending on the composition of alloying elements, different systems can be obtained. First we consider a composition of 10% B and 90% A. This composition is referred to as an all-alpha system. If cooled under equilibrium conditions, the final solid solution will be of 10% A and 90% B since it under its final cooling stages only passes trough the alpha region. See fig3

![Figure 3 Binary phase diagram of metals A and B with partial solid solubility [Ref 2]](image)

If an alloy of composition 20% B and 80% A is considered (see fig3.4), the result will in some ways differ. When the composition is cooled to a point T₃, solid beta phase begins to precipitate from the alpha phase, and two phases are present, thus this is called an alpha-beta system. At room temperature both phases are present, and in this specific compound the distribution is 88% alpha and 12% beta. This is calculated with the Lever Rule as shown below.

% Solid alpha = \((95-20)/(95-10)*100 = 88\%\)

% Solid beta = \((20-10)/(95-10)*100 = 12\%\)
The alpha phase then consists of 10% B and 90% A, and the solid beta consist of 95% B and 5% A according to the solvus lines in fig4. One aspect that is important in this system is that the horizontal line describing the composition never passes through the area, underlying the eutectic temperature line. Should the alloy have a composition, that in its cooling range under equilibrium conditions passes through the latter, a eutectic reaction takes place. See figure5.
The considered alloy has the composition of 30% B and 70% A. This is the composition existing over the liquidus line. At temperature $T_3$, which in this case is the eutectic temperature, the liquid has followed the liquidus line to point O, where it now has the composition 60% B and 40% A, and the solid has followed the solidus line to point N, where it has the composition 20% B and 80% A. At this point, the remaining liquid will solidify simultaneously, containing both alpha and beta phase.

There are some other examples of reactions that can occur when alloying Ti, for example the peritectic reaction. This is a sort of reaction that in some ways reminds of the eutectic reactions, but they can under the peritectic point contain areas in which alpha, beta and combined phases can precipitate.

**Alloying Titanium**

How desirable the properties of a pure metal are, they can always be improved. The alloying systems shown in the previous chapter depicts the mixture of materials with fairly similar chemical properties. This however is not always the case. Some metals, when they are alloyed, can form different solutions and compositions even though they are already solidified. This depends on the temperature, cooling rate and the materials in the system. On its way from liquid to room temperature, the materials will form intermediate phases and intermetallic compounds. Every alloying system should be viewed separately with respect to the material included. Even though many materials do have similar properties in alloying systems, such as the binary alloying metals displayed in the section “Binary systems”, one system should not be used as a guideline to predict the behavior of another.

**Isomorphous alloys**

Fig6 displays a system of Ti-Mo, which is a bcc-structured metal in solid state. This material, along with others e.g. Nb, Ta, V, has complete solubility in bcc-Titanium, but poor solubility in hcp. As seen in fig6, any concentration of Mo exceeding one percent will result in an all beta solid-state solution. What this reveals is that this material promotes and stabilizes the beta phase, hence it is called a beta stabilizer. This is an important factor in Ti-alloying science, and will be further discussed in later sections.
Eutectoid alloys
The Ti-Fe system displayed in figure 7 is an example of a eutectoid alloying system. The eutectic temperature is at 595°C, and the point is located at 17% Fe. In this system the different phases forms the intermetallic phases TiFe and TiFe₂. At the eutectic distribution there is a solid transformation from an all beta phase to an alpha + intermetallic phase. This reaction can be written as:

\[ \beta \leftrightarrow \alpha + \text{TiFe} \]

These phases are in most practical cases limited in order to prevent instability and embrittlement problems. Examples of other materials, which have these properties, are Beryllium, Chromium, Cobalt, Copper, Nickel and Silicon.
Peritectoid alloys
The peritectoid alloying systems are highly interesting, especially the Ti-Al system showed in figure 8 since Aluminium is a frequently used element in Ti alloying. Other metals included in this category are Carbon, Cerium, Germanium, Nitrogen, Oxygen and Tin.
In the Ti-Al system there is a variety of solid-state solutions available depending of solvent concentration, and there are some new phases occurring as well. In order to obtain a stable alpha phase, the Al concentration should not exceed 6%. If this however is done, precipitation of alpha₂ (Ti₃Al) can be detected. If the Al concentration is increase even further, an all alpha₂ state and eventually gamma phase (TiAl) is formed. Since moderate mixture of Al in Ti forms a stable alpha phase, Al is known as an alpha stabiliser.

Ti is included in a material group called transition elements. This group of elements, which are all metals, range from atom number 21 through 28, where Ti has number 22. They are characterised by their high strength and allotropic behaviour. Titanium also shows favourable alloying behaviour when alloyed, with possibilities to control the properties. The problem that can occur when handling Ti in alloying and smelting operations is its reactivity. Titanium is an extremely reactive metal, and reacts with virtually any material that it comes in contact with at an elevated temperature. This makes the handling and processing in many applications quite complicated and special precautions must be taken. If however unwanted reactions are prevented, titanium can
be alloyed with a lot of different solvents and its phases can be properly controlled [Ref 3].

**Solvents**

In general, a separation is made between three types of solvents in Ti-alloys. They are alpha stabilisers, beta stabilisers and neutral additions.

**Alpha stabilisers**

Alpha-stabilisers increases the temperature range in which alpha phase can exist. One example of a typical alpha stabiliser is aluminium. Aluminium as an alpha stabiliser replaces Ti atoms while maintaining a hcp structure. This property generates some other phases that can occur in the alloying system. As in other systems Al creates something called an intermediate phase. Ti₃Al(α₂) and TiAl(γ) are examples of intermediate phases. The γ phase begins to precipitate at higher Al contents [Ref 3].

One of the effects from Al in Ti is that it greatly increases its strength. The strength and ductility is very good up to approximately 8% Al. At this concentration the α₂ causes embrittlement. The amount of Al should always be compared to other alloying elements in the same system, since many commercial Ti-alloys are compositions of several elements all optimised in relation to each other, and to obtain specific engineering properties. For example Ti-5Al-2.5Sn, Ti-6Al-4V, Ti-6Al-2Sn-4Zr-2Mo, Ti-6Al-2Nb-1Ta-0.8Mo and Ti-8Al-1Mo-1V are all alpha-stabilised commercially available alloys. The Ti-Al alloying system can be viewed in fig8 [Ref 3].

**Beta stabilisers**

Beta-stabilisers on the other hand stabilises the beta phase. It depresses the lower limit temperature in which the phase can exist. An illustrative example of a beta-stabilised system is the Ti-Nb system showed in figure9. As the beta Titanium, as well as the Niobium has a bcc structure, and Nb is completely miscible in Ti, it is called a beta isomorphous system. What the Ti-Nb phase diagram shows is that for a moderate concentration of Nb, alpha and beta can coexist in the normal working temperature range of titanium (up to around 600°C), and for higher concentrations (>56%Nb) 100% beta Ti is stable down to 400°C. Other examples of β-isomorphous alloying elements are V, Ta and Mo.
As a complement to beta-isomorphous systems, there are systems called beta-eutectoids. The Ti-Fe system is a system of that character. As previously mentioned, the eutectoid temperature is at 595°C. See figure 7.

There are a lot of beta-stabilising elements, some have favourable properties and some should be avoided. One element that has been a major problem is Hydrogen. It can occur in Ti sponge or be the result of air contamination at elevated temperature. It generates a hydrate phase (delta), which can cause serious embrittlement problems and fatigue failures. In order to obtain some security and protection against hydrogen embrittlement, various elements can be used. Al increases the Hydrogen embrittlement tolerance in a good way. 7%Al increases the necessary Hydrogen level from 55ppm to more than 300ppm before the Hydrogen can cause any embrittlement. Another method is to alloy the Ti with small concentrations of beta-stabilising elements such as V or Mo. These elements stabilise a small amount of beta phase to room temperature, and since the hydrogen solubility is greater in beta Ti, the Hydrogen will be concentrated in the beta Ti and the Hydrogen tolerance is increased.
Neutral additions
The third kind of alloying elements are called neutral additions. The properties for these elements when alloyed are that they depress the beta-transus temperature, they have substantial solubility in both alpha and beta Ti and they make it possible for some systems to have its alpha phase present at room temperature. These elements can improve both tensile as well as creep strength, and it reduces plastic strain. Examples of neutral additions are Zr, Hf and Tin. These material have been successfully used in near alpha alloys such as Ti-6Al-2Sn-4Zr-2Mo, alpha alloys such as Ti-5Al-2.5Sn and alpha-beta alloys such as Ti-6Al-6V-2Sn. Table 3.2 displays some alloying elements and in which class they belong [Ref 3].

<table>
<thead>
<tr>
<th>Alpha stabilising</th>
<th>Beta isomorphous</th>
<th>Beta eutectoid</th>
<th>Neutral additions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Vanadium</td>
<td>Copper</td>
<td>Zirconium</td>
</tr>
<tr>
<td>Gallium</td>
<td>Niobium</td>
<td>Silver</td>
<td>Hafnium</td>
</tr>
<tr>
<td>Germanium</td>
<td>Tantalum</td>
<td>Gold</td>
<td>Tin</td>
</tr>
<tr>
<td>Lanthanum</td>
<td>Molybdenum</td>
<td>Indium</td>
<td></td>
</tr>
<tr>
<td>Cerium</td>
<td>Rhenium</td>
<td>Lead</td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td></td>
<td>Bismuth</td>
<td></td>
</tr>
<tr>
<td>Nitrogen</td>
<td></td>
<td>Chromium</td>
<td></td>
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<tr>
<td>Carbon</td>
<td></td>
<td>Tungsten</td>
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<tr>
<td></td>
<td></td>
<td>Manganese</td>
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<tr>
<td></td>
<td></td>
<td>Iron</td>
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<tr>
<td></td>
<td></td>
<td>Cobalt</td>
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<tr>
<td></td>
<td></td>
<td>Nickel</td>
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<tr>
<td></td>
<td></td>
<td>Uranium</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Hydrogen</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silicon</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 Classification of major alloying elements in Titanium [Ref 3]
**Alloy types**

Depending on what kind of alloying elements that is added to Ti, a separation between three different classes is made. The classes are:

- Alpha (or near alpha) alloys
- Alpha-beta alloys
- Beta alloys

**Alpha alloys**

Alloys that mostly consists of hcp structured Ti are classed as alpha alloys. Pure Ti is also placed in this class, even though it is not an alloy. Small amounts of beta stabilisers can sometimes be added to the system in order to increase creep strength.

These alloys consist mostly of alpha phase regardless of cooling rate. This results in a lack of response to heat treatments. They are mostly used in annealed condition, and do not have the high strength found in beta alloys. They can also create some forming difficulties, and must for example be formed with large bending radii.

Properties for alpha alloys are:

- Excellent high temperature strength
- Good weldability
- Nonresponsive to heat treatment
- Fair fabricability
- Good fracture toughness at low temperatures

**Alpha-beta alloys**

This is the largest alloy group. These alloys consist of both hcp and bcc structured Ti at room temperature. A lot of alpha-beta alloys contain Al, which increases the tensile strength significantly. The beta stabilising elements should, and in most cases they are, be kept at low level in order to promote weldability and thermal stability. Other properties are:

- Heat treatable
- Good thermal stability
- Poor weldability (when beta-stabilising content is high)
- Fair to good fabricability

**Beta alloys**
This is the smallest class, and is represented by alloys containing almost 100% bcc structured Ti. These alloys respond excellent to heat treatments, and possesses strengths exceeding 1380Mpa. They are ductile and are suitable for cold working fabrication when annealed. They do however miss the benefit of low weight, one of the properties that made Ti the success it is today. This is due to large additions of heavy beta stabilisers such as Mo, Cr and V. Properties for beta alloys are:

- Heat treatable to high strengths
- Excellent fabricability
- Excellent creep strength below 370°C
- Poor creep strength over 370°C
- Good weldability when solution treated

Figure 10 shows different alloys and places them in their class.

![Composition relationships of several Titanium alloys](Ref 3)
Metastable phases
All the previous descriptions of phases and phase diagrams have assumed equilibrium conditions. Sometimes this, for whatever reason is not the case. If an alloy’s cooling rate is to rapid, metastable phases can be formed. A metastable phase is a phase, which can exist in a transition to a more stable state. They are known as martensite, metastable beta, beta prime and Omega. Since these phases do not exist under equilibrium conditions, they do not have specific phase diagrams. These phases can be seen in ordinary alloying systems where they are marked with dashed lines. What generates these phases is when the rapid cooling rate prevents proper diffusion to take place in the alloy, which basically means that the alloy is being quenched [Ref 9].

Martensite Titanium
Martensite Titanium is referred to as alpha prime, and has borrowed its name from steel metallurgy. The reason for this is its needle shape grain structure. There are predefined temperatures for any given alloy composition, at which alpha prime begins to form and when the formation ends. They are called $M_s$ (Martensite start) and $M_f$ (Martensite finish). These temperatures are independent of cooling rate, and vary only depending on the alloy composition. An addition of amongst other Molybdenum, Iron, Vanadium and Tungsten to the alloy depresses the $M_s$ temperature. The alpha prime phase has a hcp structure and is most frequent in low alloy Ti. In high alloy Ti such as Ti-6Al-2Sn-4Zr-6Mo, an orthorhombic structure called alpha double prime can be formed. This kind of martensite is a reason for some attention, since it can reduce ductility and make the alloy brittle [Ref 9].

Metastable Beta
When a beta stabiliser is added to an alloy, there is a critical value to observe. It is denoted as $\beta_C$. This is the critical value for beta stabilisers in order to obtain 100% $\beta$ phase in room temperature. If an alloy containing a beta stabilising concentration exceeding $\beta_C$, is quenched from above beta transus, and into an $\alpha+\beta$ area, $\beta$ phase will be precipitated, where under equilibrium conditions an $\alpha$ phase would be expected, hence it is called a metastable phase [Ref 9].

Omega phase
Omega phase was first detected when some embrittlement phenomena occured. It is extremely fine and can only be seen in electron microscopes. It can be formed either athermally or isothermally. The athermal $\omega$ is formed when a level of beta-stabilisers close to $\beta_C$ is used, and the $M_f$ is below room temperature. It does not change the composition of the alloy, and has little effect on the mechanichal properties. Isothermal $\omega$ is generally formed during ageing processes. If the level of $\omega$ exceeds
50% it has been shown to cause embrittlement. In the 25-45% range it strengthen the alloy and good ductility can be achieved. If it is below 20% the effects are not noticeable [Ref 9].

**Beta prime**
If an alloy is stable enough to prelude martensite and omega, the metastable beta retained in the system can experience a phase transformation. It goes from β phase to a combination of β+β’. Both have a bcc structure. It is like omega extremely fine, making it invisible to ordinary optics. If aged, it will undergo a transformation to hcp α and a rapid increase in hardness can be seen [Ref 9].