LUND UNIVERSITY
Faculty of Science

Titanium alloys
Mechanical properties & microstructure transformation

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Abstract

The aim of the project is to determine the mechanical properties and the microstructure with α to β transformation of the titanium alloy Ti-6Al-4V. The experiments made were tensile tests at temperatures 20, 400 and 800°C and SEM images before and after inductive methods. Ti-6Al-4V is one of the most used types of alloy mainly because it has good qualities in strength, corrosion resistance and low weight with respect to the strength of the material. The strength is dependent on the microstructure and the ratio between the different phases α and β. This is the reason it is interesting to measure the transformation between the phases and then use the data to simulate and determine the required conditions for the manufacturing process. The images of the microstructure were unfortunately not ready in time for the project deadline. Instead, connections between the mechanical properties measured and other SEM images taken were done. The connections must therefore be viewed strictly as interpretations from the writer based on the work of others. The interpretation gives more questions and what one should focus new experiments on. The material structure changes with temperature and the macroscopic measurements such as stress and strain also change with the temperature. As expected there are connections between the microscopic structure and the macroscopic properties. In this thesis one can read about the material and properties of the material. There is a section about the microstructure and the phase transformation between α and β. The experiments are explained in the methodology section and the results are given and discussed. An outlook is included where future experiments and new questions to be posed are discussed.

Acknowledgments

I would like to thank the company IUC-Olofstrôm and especially the VD Magnus Liljegren for letting me do my project with them. I would also thank my supervisors for helping me with the project and the support they gave me. A big thank you to Stefan Hansson who made it possible for me to make contact with the company. And last but not least thank you Sofie Hansson (my girlfriend) for supporting me during the hard work of this project.

ACRONYMS AND ABBREVIATIONS

- SEM BSE : Scanning electron microscope, Back-scattered Electron Detector
- DIC ARAMIS : Digital image correlation with the Aramis software for correlation techniques.
- Allotropic : The existence of two or more crystalline or molecular structural forms of an element that have different chemical or physical attributes.
- Ti-6Al-4V : Titanium alloy with 6wt% Aluminum and 4wt% Vanadium. Where wt% is defined as the weight percentage.
- bcc : Body centered cubic crystal structure.
- hcp : Hexagonal closed packed crystal structure.
- α : The name of the type of phase of grains containing hcp structure
- β : The name of the type of phase of grains containing bcc structure
- microstrucure : Through the thesis I talk about the microstrucure as the grain structure where the grains are areas where the atoms are arranged in crystal structures.
- Martensite : Needle like microstructure named after the German metallurgist Adolf Martens (1850-1914) is a form of crystal state formed by diffusion less transformation, [1][2].
- acicular : refers to needle like crystal structure.
- equiaxed crystals : Crystals with axes of approximately the same length.
- Grain boundary : Boundaries between grains.
- IR : Infra read
- Thermo-couple : A device that measure temperature.
- PID : proportional-integral-derivative controller

Contents

I. Introduction

The project aim is to determine the material properties of a titanium alloy namely Ti-6Al-4V. This alloy is used in aerospace components, airplanes and surgical instruments. More precisely, one uses the material in engines because it can withstand high temperatures, and it has a good corrosion resistance, further the material has a low density with respect to its strength. The project will focus on what happens when the material is tempered to 900°C and makes a tensile test at temperatures from room temperature to 900°C. The results can give an understanding of how the process of manufacturing shall be performed without changing the material structure and properties and not develop impurities and cracks.

In today's industry there is a high development rate in light-weight materials. This is because the society demands environmentally friendly transports, such as cars, airplanes and trucks. If the weight of the transportation is lower the fuel consumption will be reduced. Using titanium can be one way to lower the weight of the transportation without compensating on the strength. Unfortunately, the cost of mining titanium and produce the alloys is very high compared to other materials which are used for cars and trucks. Although the price of titanium is high, the material properties are very good and is therefore used more frequently in military, aircraft and spacecraft applications. The rotating components in the airplanes such as the jet-engine blades or the rotating parts in gas turbines are made with titanium alloys. This is because of the strength efficiency and metallurgical stability at high temperatures which some titanium alloys provide. To manufacture such alloys and get the properties required, one needs to have control over the homogeneous microstructure and total freedom from melting imperfections such as alpha segregation. However, the greater the control is the greater the cost will be, [1]. Therefore, modeling the process of microstrucure evolution important to optimize the manufacturing process.

The goal of the project was to test and analyze the mechanical properties of a titanium alloy called Ti-6Al-4V, and to investigate what happens with the micro-structure in the material when heated and tensile tested. At room temperature the alloy is very hard and has low ductility, see figure 1; this induces problems in the manufacturing of parts. The solution to the problem is thermomechanical forming, where the tools in the press heat the material when the forming occur; when the alloy is heated to more than 700 °C, it has a low yield strength and thus high formability. The stress-strain was measured at different temperatures (20, 400, 800 and 900°C) with the ARAMIS system and a tensile test machine. The microstructure images were taken using SEM BSE at Lund University and Oxford University both at room temperature and at 900°C.

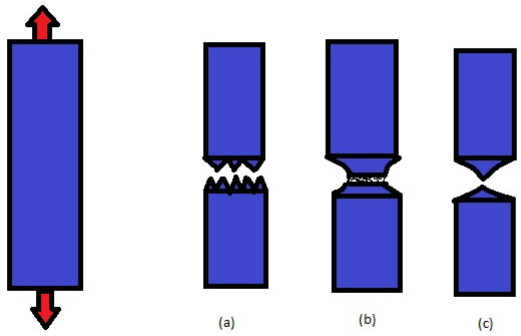

Figure 1: *Figure shows a tensile test of materials with different ductility ranching from (a) low ductility, (b) higher ductility and (c) Highest ductility.*

II. Theory

In the following theory section, the description of the material will go from a macroscopic classical level to an atomistic level.

I. Stress-Strain curve

A number of mechanical properties of Ti-6Al-4V can be determined with the stress and strain curve and, how the stress and strain are determined is described below.

The strain is given by the time dependent deformation of a uniform material that is experiencing stress, [5]. The engineering strain is given by

$$\epsilon_e(t) = \frac{L(t) - L_0}{L_0} \tag{1}$$

$L(t)$ is the length of the specimen at a given time and L_0 is the length at time zero. The logarithmic strain or true strain is then given by integrating the incremental strain which is

$$\delta\epsilon = \frac{\delta l}{l} \tag{2}$$

where l is the final length after deformation. Then integrating this gives

$$\int \delta\epsilon = \int_{L_0}^{l} \frac{\delta l}{l} \tag{3}$$

$$\epsilon = ln(\frac{l}{L_0}) = ln(\lambda) = ln(1+\epsilon_e) = \epsilon_e - \frac{\epsilon_e^2}{3}.... \tag{4}$$

and λ is the elastic modulus or Young's modulus which is defined as the slope of the stress-strain curve.

The strain rate is then

$$\dot{\epsilon}(t) = \frac{d\epsilon}{dt} = \frac{d}{dt}\Big(\frac{L(t)-L_0}{L_0}\Big) = \frac{1}{L_0}\frac{dL(t)}{dt} = \frac{v(t)}{L_0} \tag{5}$$

$v(t)$ is the speed that the two ends are being pulled away from each other.

The stress is force divided by area

$$\sigma_e = \frac{F}{A_0} \tag{6}$$

where F is the force and A_0 is the original area. This equation gives the engineering stress. The area is not the same through out the tensile test because when the pull force is applied the material is deformed and gets longer in the pull direction as well as shrinks in thickness and width. So the true stress is calculated using the relation

$$\sigma_{true} = (1+\epsilon_e)\sigma_e \tag{7}$$

One can also use the equation for engineering stress to calculate the true stress but using the true area through the calculation.

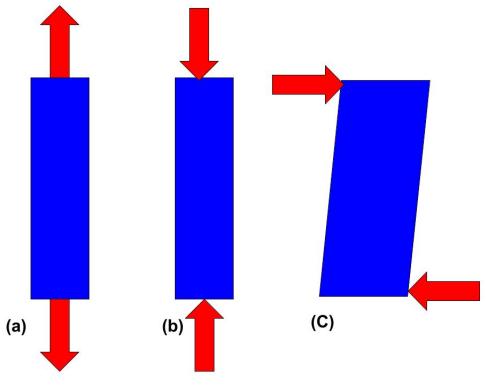

Figure 2: *Figure shows (a) tensile stress, (b) compression stress and (c) shear stress.*

As seen in figure 2 there are different types of stress; tensile stress, which is the type focused on in the experiments and is defined as the force perpendicular to the cross section of the material pointing out from the material, [5];; compression stress which is the type of stress when the material is compressed by forces pushing the material inwards perpendicular to the cross section, [5];;; shear stress, when the force is applied parallel to the cross section of the material, [5].

The stress-strain curve is a curve where the x-axis is the strain and the y-axis is the stress and is used to describe the deformation of materials and determine the break point, r-value, n-value, yield, elastic and plastic region and the maximum stress of the material, see figure 3. The stress-strain curve gives the information of the materials different states. For example if the material is in the elastic region or has crossed the yield point or if it is in the necking region after it will break.

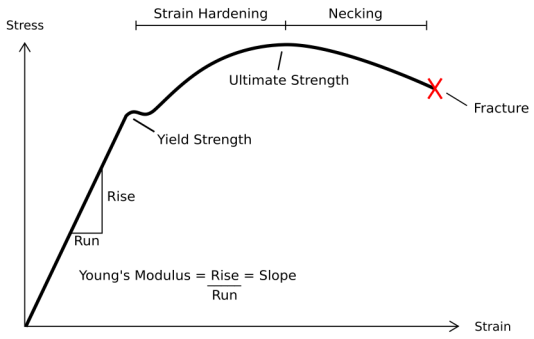

Figure 3: *Figure shows the stress-strain curve with several regions and points marked. Courtesy to FSF (Free software foundation).*

II. r-value

The r-value is the ratio between the deformation of the thickness and the width of the specimen. Specifying how much material that is taken from the thickness and the width to the elongation in the length. The r-value is given by

$$r = \frac{\epsilon_w}{\epsilon_{th}} \tag{8}$$

where ϵ_w is the strain in the width direction and ϵ_{th} is the strain in the thickness direction.

III. n-value

The n-value is the material strain-hardening coefficient and is used to describe the plastic flow of solids, [3].

$$\sigma = K\epsilon^n \tag{9}$$

where K is the strength coefficient. The n-value can also be determined from the stress and strain as

$$n = \frac{\epsilon}{\sigma}\frac{d\sigma}{d\epsilon} \tag{10}$$

IV. Microstructure

The microstructure of a material is often defined in material science as the grains of the crystal structure. The atoms in the material are arranged on lattice structures which then form groups of similar structure into grains. The orientation of the lattice generally differs over distance unless one grows a single crystal, [1]. The orientation of the lattices is the same within each grain with the distance but over the boundaries the next grain will have a different spatial orientation. Titanium is an allotropic element, which means that it exist in several crystallographic forms. At room temperature it has a hexagonal close-packed (hcp) structure (this state is defined as an α phase). Besides, there exists a small fraction of body centered cubic (bcc) crystal structure, which is called the β phase, see figure 4. However, at higher temperatures the α phase grains change their binding and they become bcc type β phase grains.

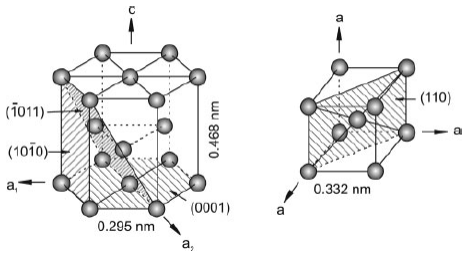

Figure 4: *Figure shows the hcp (α) and bcc (β) structure for pure titanium. The small balls are the atoms in the structure and they are bound together by the metallic bond, [2].*

Transformations from one phase to the other are mostly described as β to α because, when manufacturing metals, the metal is heated up and then shaped to the wanted tool form and then cooled. The cooling rate affects the properties of the material and is therefore important. The cooling rate affects the transformation for the β to α phase and the ratio between the two phases determines the properties of the material, [2]. The driving force of the transformation is the difference between the Gibbs free energy of the initial and final state. The Gibbs free energy is defined as the thermodynamic potential which depend on the temperature and pressure, [8][2][4].

$$G = H - TS \tag{11}$$

where H is the enthalpy, T is the temperature and S is the entropy of the system. The enthalpy is a measure of the heat content of the system and is given by $H = E + PV$ were E is the internal energy which is the kinetic and potential energy of the system, P is the pressure, and V is the volume, [9].

The most densely packed bcc β phase $\{110\}$ transforms into the basal plane $\{0001\}$ hexagonal α phase. The distance between the basal planes in α is larger than the corresponding planes in the β $\{110\}$ structure. This difference in distance leads to a distortion in the atomic configuration because of the β to α transformation. The atomic distortion then leads to a small contraction in the c-axis relative to the a-axis in the hcp α lattice which reduces the ratio c/a below the value of ideally hexagonal closed packed atomic structure, [2].

The directions of the of the so called slip deformation can be described by the Burgers relationship, see figure 5, where the directions are the Burgers vectors. The Burgers vectors describe the magnitude and direction of the distortion in the lattice which results from a dislocation, [4]. The transformation from one phase to another is the result from such a distortion often by the slip of one plane. The slip of a plane can then result in another type of Bravais lattice because

the structure of the lattice between the planes change.

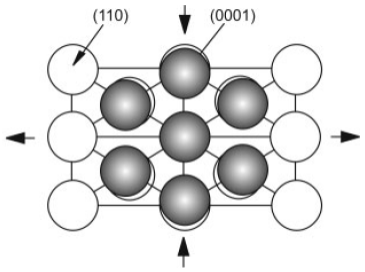

Figure 5: *Figure shows the β to α transformation according to the Burger relationship, [2].*

A model that describes this transformation from α to β structure originates from kinetic theory of matter which describes the thermodynamic flow from one phase to another. An example is the modified model of Johnson-Mehl-Avrami (JMA) which is described below. However, the thermodynamic theory describes the grains and not individual atoms. The JMA model is used to calculate the amount of one type of phase relative to the total volume and the amount after heating or cooling the material.

The change in volume of α or β grains is calculated using the following formula, [7].

$$\Delta v_\alpha = -\delta v_\beta = \left(1 - e^{-B_{\beta\alpha}(t_c+\Delta t)^{N_{\beta\alpha}}}\right)(v_\beta^n + v_\alpha^n)v_\alpha^{eq} - v_{alpha}^n \tag{12}$$

where v_β^n is the volume fraction of β phase available for the transformation and v_α^n is the equilibrium volume fraction of the α phase to be formed. B and N are JMA kinetics constants which vary with temperature and they depend on the material and can be found in the literature. Δt is the time step at which the temperature increases with. The time t_c is given by

$$t_c = \left[-ln\left(1 - \frac{v_\alpha^n / v_\alpha^{eq}}{v_\beta^n + v_\alpha^n}\right) / B_{\beta\alpha}\right] \tag{13}$$

If one uses these equations and plots ΔV_α and ΔV_β against the temperature one sees how the volume of α phase decreases at the same rate as the β phase increases, see figure 6

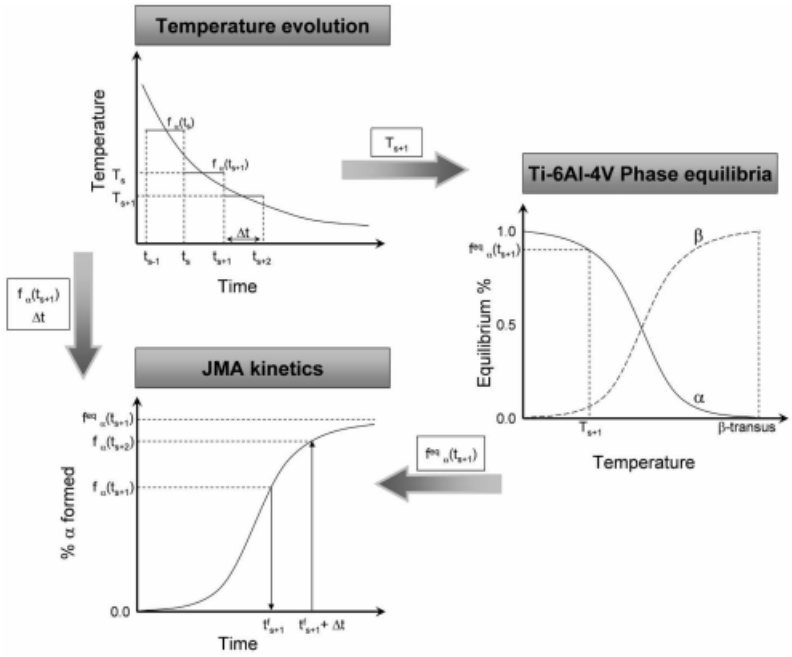

Figure 6: *Figure shows a generalization of the JMA model for a anisothermal transformation in Ti-6AL-4V, [10]. Notice the phase equilibrium in the right diagram were one sees how one phase transfers into the other when changing the temperature of the material.*

III. METHODOLOGY

The methodology section describes the preparation of the samples before doing the experiments. The experiment done was the uniaxial tensile tests and the SEM images both taken at Lund University by the division of syncrotron radiation and at Oxford University.

I. Sample preparation

The sample preparations were done by measuring the thickness and width at the midpoint and at an upper and lower point in the range of 25 mm around the midpoint, see figure 7. The samples was sandblasted to rough the surface structure for the paint to better grip on the specimen. For the Aramis system to be efficient the samples were painted with a white color (heat resistant to handle 900°C) and a black paint to make the stochastic speckle pattern with aerosole. The black paint worked up to 700 to 800°C and it was therefor necessary to use another paint which was temperature resistant, the painted specimen is shown in figure 8.

The speckle pattern is important because the Aramis system uses the pattern to follow the deformation of the specimens as they are pulled in the tensile test machine.

Figure 7: *Figure shows the sandblasted but not yet painted specimen where measurements of thickness and width has been done.*

Figure 8: *The figure shows the painted white background and the stochastic black pattern on the specimen. One can also see the thermo-couple that is welded on the back.*

II. SEM BSE

Scanning electron microscopy produce images of the micro-structure of a sample. This was done both before and after heating to 900°C. Samples were also sent to Oxford University where they performed SEM while heating up the specimens. The SEM uses a focused electron beam that scans the material and uses the back-scattered electrons to form an image of the surface, see figure 9. The image is built on the energy of the electron as well as the angle at which they enter the detector. With this information together with the position of the outgoing beam the image can be produced with an resolution less than 1 nm.

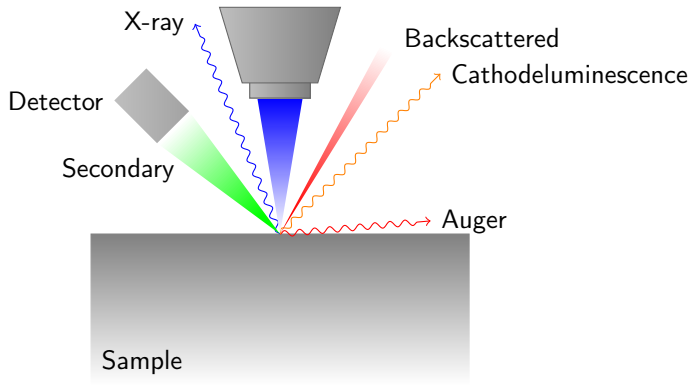

Figure 9: *Figure shows the concept of scanning electron microscopy. One also see different types of radiation that is produced by the electrons interacting with the surface, such as Auger signal which is electrons emitted from the atoms that the incoming electron collided with and X-ray which is photons emitted from the atoms when the electrons collide with the atoms.*

III. Tensile test, DIC with ARAMIS

A uniaxial tensile test was done at four different temperatures, as it can be seen in table 1. The tensile machine was first checked so that the displacement between the clamps that holds and pulls the samples was 21 cm which is the original length before the test. The IR sensor was calibrated using a thermo-couple (type K) connected to the specimen which measures the temperature generated by the induction coil and the values are used to calibrate the IR sensor. The sample was first placed in the upper holder of the tensile machine at a mark on the sample and the machine was then set to zero force and the lower holder was set to clamp the sample. This position was now set as the zero position for the machine and from this position the lower holder pulled the specimen when the desired temperature was achieved. The machine can be seen in figure 10 where the upper and lower holders are shown.

A strain rate of $0.1\,\mathrm{s}^{-1}$ corresponds to a speed of $2.5\,\mathrm{mms}^{-1}$ and a strain rate of $1.0\,\mathrm{s}^{-1}$ corresponds to a speed of $25\,\mathrm{mms}^{-1}$. The strain rates were used to set the speed of the lower grip of the tensile test machine.

Table 1: *Table shows the temperatures tested and at which strains.*

Temperature [C]	Strain rate [1/s]
20	0.1
20	1.0
400	0.1
400	1.0
800	0.1
800	1.0
900	0.1
900	1.0

Figure 10: *Figure shows the tensile test machine*

The ARAMIS system is a system which uses images taken from two cameras to measure the 3 dimensional deformation of a material as it can be shown in figure 11. The Aramis system makes a correlation between the images by using a facet which is a small box that one sets before starting the computation. The program then tracks the facets movement through out the images during the deformation. With the information from the tracking the program use algorithms to calculate the deformation in percents [11].

From the correlated images the software calculates several quantities e.g. the stress and strain.

Figure 11: *Figure shows the cameras and lights that take the images for the ARAMIS camera and strain measurement system.*

The induction coil used to heat the specimens is an interesting piece of equipment and the physics that describes the effect is even more interesting. An alternating magnetic field produces an electric field in the material. The electric current (or eddy currents) are converted into heat.

This effect is seen in conductive materials. When a magnetic material is affected by the inductor the magnetic fields produce an internal friction from an effect called hysteresis [12]. The heating of a magnetic conductive material is faster because of the hysteresis effect.

The law which describes the effect is called Faraday's induction principle and states "The induced electromotive force in a closed loop equals the negative rate of change of magnetic flux through the loop",[13], see equation 14.

$$E = -\frac{d\Phi_B}{dt} \tag{14}$$

where E is the electromotive force, Φ_B is the magnetic flux and t is the time. So the faster the magnetic field change the larger electromotive force.

The coil is placed only a few millimeters from the specimen to get a good and even heating. The coil is controlled with a computer with which the wanted temperature and PID regulator parameters were controlled. The PID regulator or controller is a device that controls a signal via a controlled loop feedback mechanism. P is the controller which continuously calculates the error temperature value between the wanted value and the measured process variable. When the error is calculated the controller adjusts a variable for the purpose of minimizing the error. In the case of the induction coil it is the power supplied to the heating element. The minimization is done with a weighted sum given by

$$u(t) = D_p e(t) + D_i \int_0^t e(\tau)d\tau + D_d \frac{de(t)}{dt} \tag{15}$$

where D_p, D_i and D_d are all positive and denote the coefficient of the proportional, integral and derivative terms respectively. e is the time dependent error function $e = sp - pv$ where sp is the set point and pv is the process variable. t is the instantaneous time (present) and τ is an integration variable which takes a value between 0 and t. The proportional term P produces a term proportional to the current error value $P_{out} = D_p e(t)$ and depending on the value of p the output signal can become unstable if the value is to high or not sensitive to disturbances if to low. The Integration term I accelerates the process to achieving a small error $I_{out} = D_i \int_0^t e(\tau)d\tau$ by accelerating the movement of the process towards the set point which for example means the wanted temperature of the induction coil. The integration term is also responsible for the "overshoot" over the set point. The derivative term D gives more control and stability to the system with $D = D_d \frac{de(t)}{dt}$, [14]. The parameters influence how fast the temperature increase and how much "overshootÂťÂť the temperature goes over the needed temperature. Before the tensile

tests started the temperature had to be steady around the necessitated temperature meaning as little fluctuations as possible, see figure 16.

IV. Results and Conclusions

Through my search for information about the science describing different properties of materials I have come too the conclusion that there is much work left to be done for new scientists such as myself. The material science today is almost conclusively done experimentally and there are not much theories developed that describes the materials properties completely from the microscopic scale (where quantum mechanics is used) to the macroscopic scale (where classical mechanics is used). Many theories that have been developed throughout history began first as empirical studies from which theories later sprung from. As experimentalist, I have made experiments and will draw conclusions and make interpretations from the results of my experiments. The Interpretations and conclusions I make are inspired from the work of others such as S. Semiatin, D. Raabe, M. Avrami and B. Babu, [15][16][17][18][19][20][21][22][23].

The question I asked myself is what is the driving factor that changes the material behavior at different temperatures? And is the driving factor connected to the microstructure of the material

The tensile tests gave interesting results about the temperature dependence on the ductility and yield strength. When looking at the tensile test diagram (see figure 13) one can see that the stress decreases with increasing temperature. The explanation for this is not easy and there is no complete explanation for large systems in anisotropic crystals such as Ti-6Al-4V. However, classical theories were adequate for room temperature but for cryogenic temperatures quantum mechanics is required. Quantum mechanics provides explanations for atomic vibrations also called phonons for low temperature and as the temperature increases the amplitude of the vibrations increase which means that the number of phonos increase, [4]. With the knowledge of the quantum mechanical description I made the interpretation that when increasing the temperature the energy of the atoms in the material increase. The increase in energy produces lattice vibrations, or thermal vibrations, and the vibrations results in easier deformation when applying stress, [2] [24].

The material tested has two types of structures and the ratio between them depends on the temperature. At room temperature there is typically over 90% α type structure and as temperature increases so is the volume of β type structure up to a certain temperature where there is 100% β

phase structure, see figure 6. The transfer from one type to the other is connected to the thermal vibrations and is described as a thermodynamic concept, see section IV. The α type structure is close packed and has a smaller energy density than the β type structure; this can explain why the material have such different properties at different temperatures and why the ductility increases with temperature. The ductility means the degree of formability of the material and because β type structure is not as closely packed as the α type the deformation is much easier.

In figure 12 one sees an example how the microstructure transform depending on how much the material is heated and cooling technique. It also shows how the alloying material Vanadium works as a β phase stabilizer.

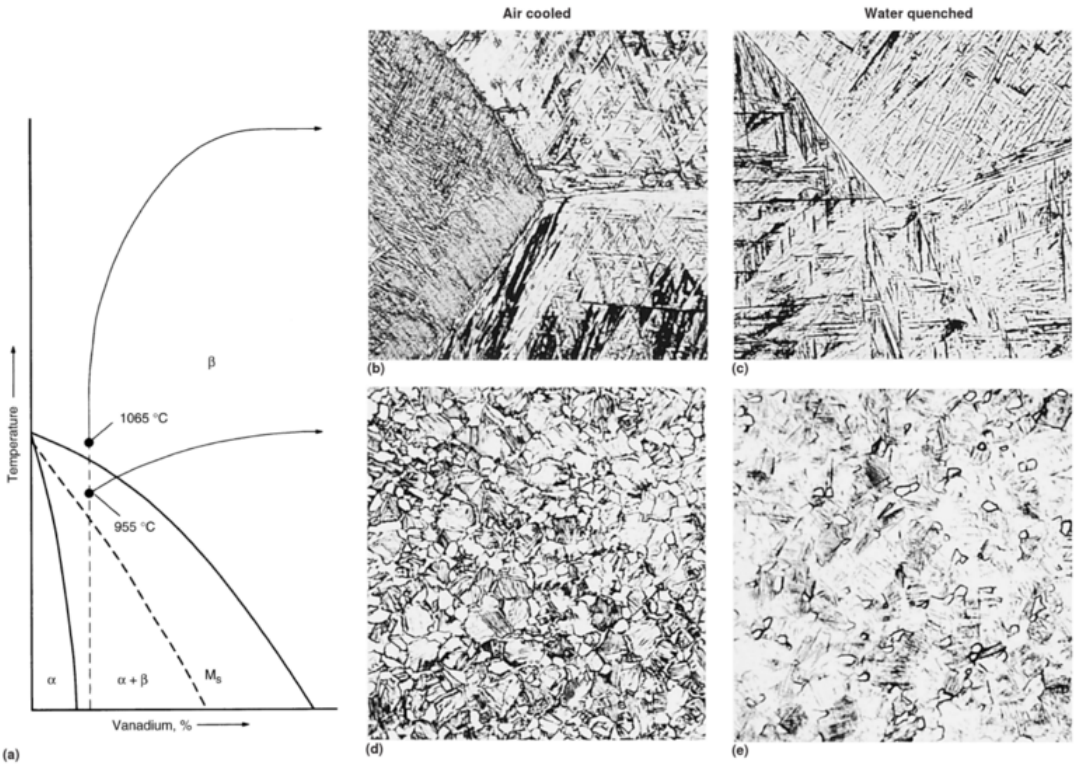

Figure 12: *Figure shows the microstructure of Ti-6Al-4V and a pseudo phase diagram. The first image (a) shows a diagram with Ti-6Al-4V composition diagram. The SEM images is for different cooling techniques. The microstructure in image (b) is acicular α grains with β grain boundaries. (c) shows martensite structure (which is the long needle like structure) with β (dark parts) and prior β grain boundaries. (d) has primary α grains (light parts) in matrix of transformed acicular α and last (e) is equiaxed primary α in matrix of alpha prime (martensite), [1].*

Unfortunately the heating of the specimen was difficult and the 900°C test was invalid. Instead more tests at 800°C where made to make sure that the test where valid. However, the tests on lower temperatures was successful and the results can be seen in figure 13.

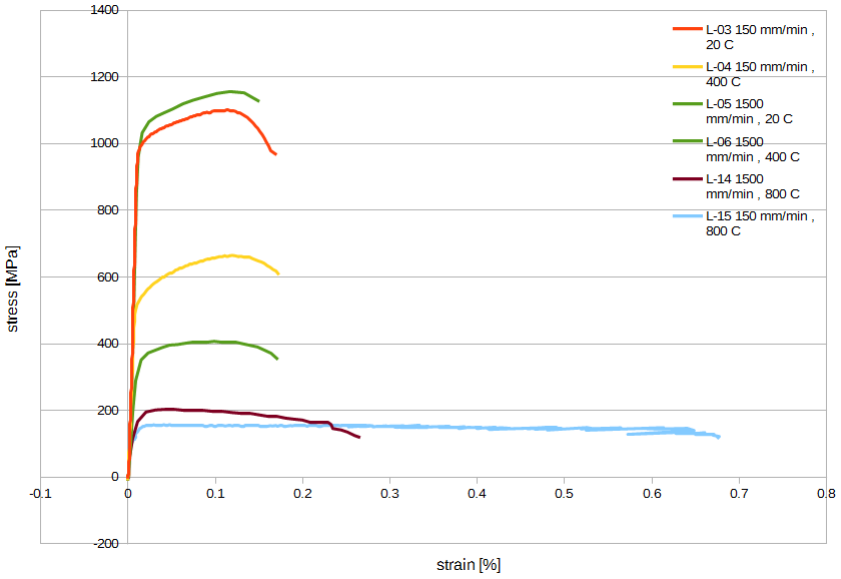

Figure 13: *Stress-strain curve for six different specimens at different speeds and temperatures.*

In the stress and strain diagram, see figure 13, one can also see that the specimen L15 is deformed much longer and has a higher strain than the L14 specimen. This is interesting and not expected and the evaluation of the data was done on more time to double check if something went wrong. It seems that all was correctly done and this indicates to something physical or an error that we did not find. To say something more one needs to do more tests to investigate if the effect.

As one can see in figure 13 the diagram shows that the stress is larger for the specimens that were pulled at 1500 mm/min. This is expected because as one can see in equation 6 the stress depends on the force and force is proportional to the acceleration which is larger for the specimens that where pulled with a faster speed. However, the specimens that were tested at 400°C do not show this behavior, which I believe is because of some misalignment of the induction coil that would heat the specimen unevenly. This can be seen in the images taken with a heat camera, see images 14 and 15. In figure 16 one can see the heating curve for the two samples measured with an IR sensor and the thermo-couple. The diagram shows that there are a large difference between the samples if one looks at the IR sensor but not if one looks at the thermo-couple. This is interesting and indicates that there could be some malfunction on the thermo-couple, meaning

that the thermo-couple maybe disconnected from the specimen. To test this one needs to make more tests at the same temperature and test with both the IR sensor and the thermo-couple and see if there is some difference. The temperature seems to be higher for the faster pulled specimen and this is an indication that the ductility and formability depends on the temperature more than the speed at which the specimens are pulled with.

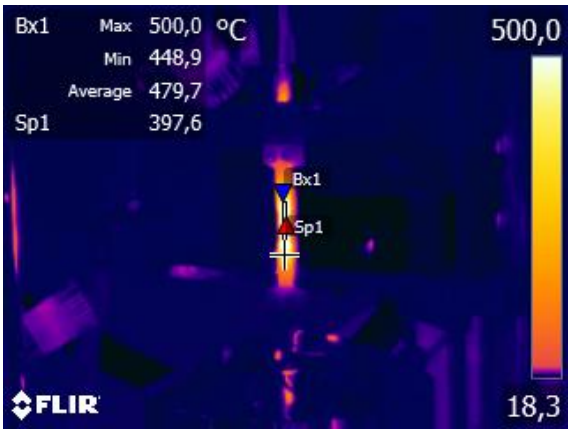

Figure 14: *Figure shows the specimen L04 which were heated to 400° C and pulled at* 150 mm/min.

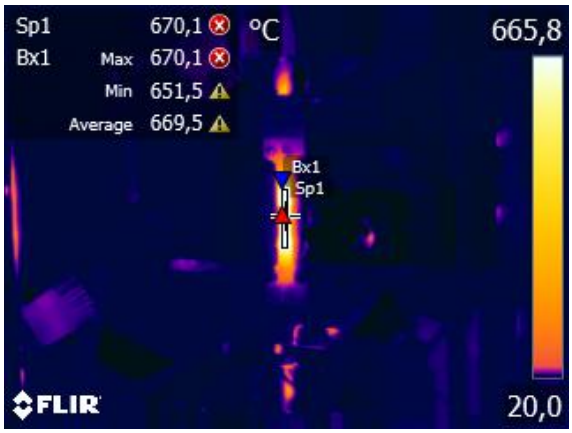

Figure 15: *Figure shows specimen L06 which were heated to 400° C and pulled at* 1500 mm/min. *But this image indicate that the temperature might be higher.*

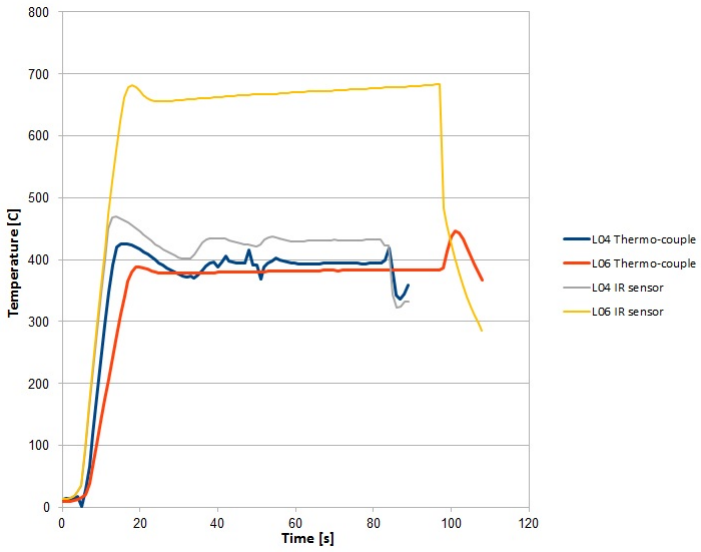

Figure 16: *Figure shows the heating curve for the two samples L04 and L06 which were heated to 400° C. The figure shows both the measured temperature from the IR sensor and the thermo-couple.*

The yield, stress, hardening, r-value and n-value are important values for the simulations of the manufacturing process.

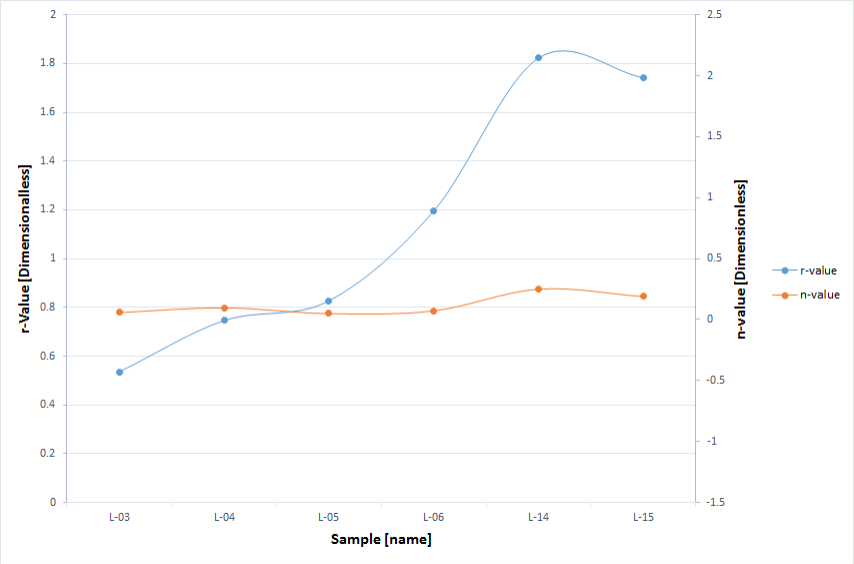

Figure 17: *Figure shows the r and n-values for different specimens.*

Figure 17 shows the r-values and n-values for the different specimens and one can read out that the n-value does not change, only small fluctuations can be seen. The n-value is the material hardening coefficient and the behavior is expected because the n-value is calculated as the slope of the stress-strain curve after the elastic region and the change is stress is not large after this point. The n-value is also dependent on the strength coefficient and the stress and strain which is illustrated in equation 9 and it can be used to calculate the strength coefficient K. The diagram also shows the r-value for the different specimens and one can see that the value increases with the temperature. This is interesting because it means that the strain in the thickness is smaller than the strain in the width for higher temperatures. The deformation in the width increases more for higher temperatures compared to the deformation in the thickness. (From this observation questions arise, why does the material deform more in the width compared to the thickness for higher temperatures? And what is the connection to the atomic scale?)

The microstructure images produced at Lund University were interesting although not what I needed. Because of a misunderstanding from my part the images does not show the grain structure which is needed to make conclusions about the phase transformations. To show the grains the sample needs to be prepared accordingly such that the surface structure is clean. The images showed too much structure and oxidation to be used.

V. Outlook

Material science has been around for more than 200 years but there is still work to be done. My project has just brushed the surface of the questions that one can search an answer to. The questions that I asked myself when starting this project was. What is the driving factor that changes the material behavior at different temperature? And is there a connection to the microstructure of the material? My experiments did not give me an answer to these questions but they certainly gave me an insight to the possibility that further investigations and experiments can give. In my searches in other scientists and engineers work I found theories and models that exists and work on specific materials and simpler material but a complete picture is not yet available for most complicated materials such as those considered in this thesis.

My studies in this project gave me the understanding enough to make interpretations that answers my questions but to be able to answer with higher certainty one needs to make further experiments. One is to have the SEM images that were not finished and also it would be interesting to measure the Gibbs free energy changes when heating the material. It would be interesting to investigate more about the lattice vibrations.

Other aspects that would be interesting to investigate is crack propagation in the material and test the electrical conductivity for different alloys to see if the different compound of elements influence the conductivity and if different temperatures change the conductivity.

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