Chapter

Microstructure and Mechanical Properties of Laser and Mechanically Formed Commercially Pure Grade 2 Titanium Plates

Kadephi Vuyolwethu Mjali and Annelize Botes

Abstract

The microstructure and mechanical properties of laser and mechanically formed commercially pure grade 2 titanium plates are discussed in this chapter. The microstructure of the as received parent material is compared to that resulting from laser and mechanical forming processes. Residual stress results from the two forming processes are analysed and bring to light changes brought about by these processes to the titanium used. The effect of the two forming processes on the mechanical properties is discussed, and the effect of process parameters on these properties is also argued in detail.

Keywords: laser forming, mechanical forming, residual stress, tensile testing, hardness testing

1. Introduction

The processing of engineering materials has become a specialist field, and this industry will continue to grow due to rising costs in raw materials which have forced many automotive and aviation industry suppliers to invest heavily in this field. In order to be relevant and competitive in today's industrial world, companies around the world are now forced to dedicate billions of dollars in profits to research and development. Many research centres are looking at titanium as a solution to some of the engineering challenges facing both automotive and aviation industries. Titanium is now finding favour with companies in pursuit of savings in fuel consumption and related improvements to mechanical properties. Savings in fuel consumption is achieved by reducing weight on aircraft and automobiles yet still meeting acceptable industrial norms and standards like improved structural integrity on the finished product. Improvements in engine and turbine design have also helped in the pursuit of fuel efficiency in these industries. In-depth research into the behaviour of titanium alloys under varying loading conditions is therefore essential in the quest to find more industrial applications of this metal. The last century saw a major development in processing and fabricating techniques. These developments were largely in part as a result of great emphasis placed in research and a continued search for improved methods in metal forming. This contributed to the development in forming techniques, materials, processing and understanding of changes a metal goes through during forming. There has always been room for improvement in the forming of materials due to the widespread use of forming operations in the automotive, aviation and shipbuilding industries. An in-depth study into the effects of laser and mechanical forming processes on the mechanical properties of commercially pure grade 2 titanium plates was conducted. This was achieved by producing a radius of curvature of approximately 120 mm on the plates with the aid of the mechanical forming machine. The plate samples were then subjected to mechanical testing to evaluate changes in mechanical properties. A Nd:YAG laser was used to replicate what had been achieved using the mechanical forming machine to bend titanium to the same radius of curvature. It was anticipated that this would lead to an extension of applications of laser forming and the possibility of increasing strength of thin commercially pure (CP) grade 2 titanium plates due to the heat treatment characteristics induced by the process. The laser forming study used established parameter settings which greatly influence the microstructure and bend radii. The intention of the study was to use both mechanical and laser forming to bend titanium plates to a final radius of curvature of 120 mm.

2. Commercially pure grade 2 titanium

Table 1 shows the chemical composition of the titanium used in this study which is weldable and formable and has excellent corrosion resistance properties. The tensile and yield strength values go up with grade number for pure grades.

Titanium can be cold rolled at room temperature to above 90% reduction in thickness without serious cracking [1]. Titanium undergoes allotropic transformation from the hexagonal close-packed (hcp) alpha phase to the body-centred cubic (bcc) beta phase at a temperature of 883°C. At room temperature, its properties are controlled by chemical composition and grain size. The presence of these elements determines the nature of the alloy and its chemical properties. The density of alpha titanium alloy falls between that of aluminium alloys (2.7 g/cm^3) and steel (7.8 g/cm^3) at 4.51 g/cm^3 as indicated. Due to the high-yield stress values of titanium, which are similar to steels and twice the strength of aluminium, makes this metal a choice in areas where weight is an important consideration [2]. An inhibiting factor especially in the automotive industry is the cost involved in using titanium as the main structural metal, whereas in the aviation industry, the manufacturers are able to include the cost of titanium in the final price of their products. The physical properties of CP titanium and properties like linear expansion coefficient, thermal conductivity and specific heat capacity playing a major role in the laser forming process are shown in **Table 2**.

2.1 Laser forming

Laser forming (LF) evolved from more mature, but less sophisticated thermo-mechanical forming processes. Specifically, manual application of an oxyacetylene

Grade	C	O_2	N_2 Max	Fe Max	H Max	Ti
Commercially pure titanium (as supplied)	0.005	0.155	0.009	0.04	0.003	Bal

Table 1.
Chemical composition of commercially pure grade 2 titanium in % wt.

Property	Linear expansion coefficient	Thermal conductivity	Specific heat capacity	Electrical resistivity	Alpha/beta transform temperature	Young's modulus	Shear modulus	Poisson's ratio	Density
Alpha titanium	8.36×10^{-6} K^{-1}	14.99 W/m.K	523 J/kg.K	5.6×10^{-7} Ohm.m	882.5°C	115 GPa	44 GPa	0.33	4.51 g/cm^3

Table 2.
Physical properties of pure titanium.

torch for forming steel plates for the ship building industry has been used for some time and is seen as the precursor to LF [3].

The laser forming process has become a choice to fabricators of metallic components and as a means of rapid prototyping and of adjusting and aligning [4]. Laser forming is of importance to industries that previously relied on expensive stamping dies and presses for prototype evaluations. Industry sectors making use of this process include aerospace, automotive, shipbuilding and those in microelectronics. The laser forming process involves no mechanical contact, which is a requisite in mechanical forming and is considered a virtual manufacturing kind of method. The laser forming process can be used to produce predetermined shapes. The process results in minimal distortion on the formed components [5]. The laser forming process can produce metallic, predetermined shapes with minimal unwanted distortion, and investigations are also ongoing in the removal of unwanted distortion resulting from the procedure.

A successful and significant research in the laser forming of materials needs a good understanding of thermal transfer concepts as they play a crucial role in the process. Concepts like conduction and thermal radiation need to be understood fully to balance all the process variables. Thermal radiation is the transfer of energy by electromagnetic waves, whereas thermal conductivity, on the other hand, is the property a material possesses indicating its ability to conduct heat. Thermal conductivity of titanium is lower than most competing metals like steel, magnesium and aluminium. This means that in order to cause changes in the microstructure, a higher intensity of heat would have to be emitted by the heat source and in this scenario by the laser. The ability of the plate material to absorb and transfer heat is the major underlying factor. This factor plays a major role in the forming of plates as the effect of conduction affects the microstructure, thereby influencing the mechanical properties. The heat flux (power density), which plays a considerable role in the laser forming process, is the amount of energy flowing through a particular surface area per unit of time and is represented by the following formula:

$$q = \frac{Q}{\pi r^2} \quad (1)$$

where q is the heat flux, Q is the laser beam power (W), r is the beam radius (m), and π is the constant.

According to Ion et al., a large number of variables influence the interaction between a laser beam and a material; over 140 variables can be identified for welding alone. In this instance, the power density will be considered when a beam is switched on. The heat flow becomes steady state, and the energy absorbed by the surface is balanced by that conducted heat into the plate, and the temperature field becomes constant. The principal process variables are the beam power, the beam radius and material properties. The power density can be increased four times by quadrupling the power or by reducing the beam radius to a half. When this variable group is identified, a smaller subset of experiments can be undertaken to establish that the power density determines the peak surface temperature attained. These factors determine the principal mechanism of thermal interaction—which could either be heating, melting or vaporisation [6]. The laser powers used, the thermal conductivity, the line energy, scanning velocities, beam interaction time and also the heat flux (power density) generated during the laser forming process are all shown in **Table 3**.

Power and scanning velocities were adjusted during the preparation of plate specimens used in this study and the other given parameters resulted from these adjustments (beam interaction time, heat flux and thermal gradient). The heat flux formula was considered for analysis in order to understand the concepts involved in this process. The laser power ranged from 1.5 to 3.5 kW for the specimens evaluated, and an increase in power resulted in an increase to the heat flux and line energy generated. With the arrangement used, the samples are not clamped in any way, and the line heating application alternates in succession from each end incrementally moving towards the centre of the plate. The open mould method shown in **Figure 1** was used in the laser forming of the CP grade 2 titanium plates.

The beam interaction time was an important factor in the analysis of the resulting microstructure and can be determined by the formula

$$t = \frac{2r_b}{v} \tag{2}$$

The variables $2r_b$ and v represent the beam radius and the scanning velocity, respectively. The power density, beam radius and beam interaction time play a considerable role as they determine whether the material will be cut, welded, melted or hardened. The heat flow in laser processing can be complex, but for many processes it may be approximated to three fundamental conditions: steady state, transient or quasi-steady state. Fourier's first law describes steady state conditions as

$$F = -\lambda \Delta T \tag{3}$$

where F is the heat flux ($W/m2$), ΔT is the thermal gradient (K/m), and λ is the thermal conductivity ($W/m.K$). In this state, the temperature field does not change with time at a location in a material. The thermal gradient is a physical quantity that describes in which direction and at what rate the temperature changes most rapidly around a particular location. The thermal gradient can lead to different amounts of contraction in different areas, and if residual tensile stresses become high enough, flaws may propagate and cause failure. A lower thermal gradient may cause bending in other engineering materials but due to differing thermal conductivities may not work in other materials. This means that each engineering material needs to be isolated in the analysis of its physical properties. For example, what may work for steel may not be applicable to titanium due to different thermal conductivities of the two materials. Line energy is a concept used by engineers and scientists in laser forming to control bending characteristics of plates. According to Magee, the energy input to the sheet-metal surface critically affects the nature of the process and forming mechanisms which take place [7].

The line energy specified by Magee is a function of laser power and the scanning velocity. In determining the process parameters for the experimental exercise, four sets of power levels believed to result in the desired curvature were chosen and are listed in **Table 3** and discussed here. The laser forming process produces large thermal gradients that could either bend or shorten the material. The bending or shortening of the material is a result of the line energy produced by the laser and is given by the formula

DOI: http://dx.doi.org/10.5772/intechopen.81807

Laser power (kW)	Thermal conductivity (W/m.K)	Line energy (kJ/m)	Scanning velocity (m/min)	Beam interaction time (sec)	Heat flux ($\times 10^6$ W/m^2)	Thermal gradient ($\times 10^3$ K/m)	Beam diameter (mm)	Average radius of curvature (mm)
1.5	15	35	2.62	0.0091	13.3	221	12	180.1
1.5	15	47	1.9	0.0122	13.3	221	12	150.3
2.5	15	90	1.7	0.0141	22.11	1474	12	134.3
3	15	90	2	0.0121	26.53	1769	12	118.4
3.5	15	90	2.3	0.0101	31	2064	12	106.1

Table 3.
The various parameters involved in the laser forming process.

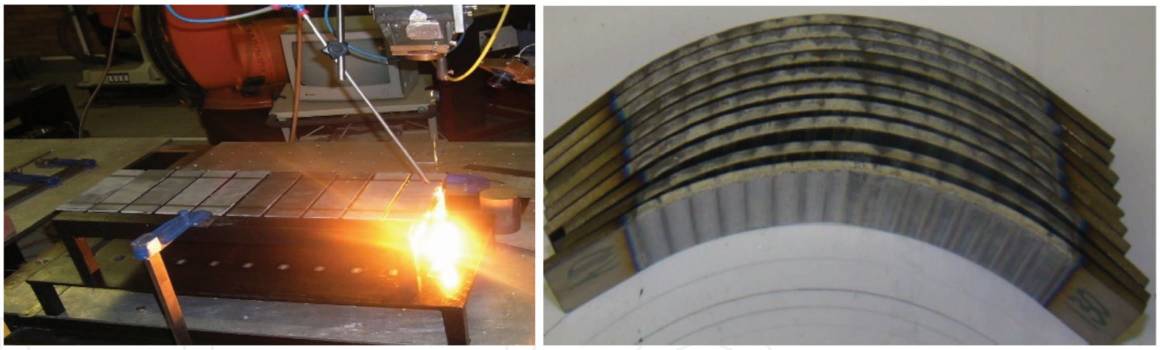

Figure 1.
Laser formed CP grade 2 titanium with the open mould arrangement.

$$L = \frac{P}{v} \tag{4}$$

where P represents laser power in Watts (W) and v represents the scanning velocity in metres per minute, respectively. Line energy is the most important variable in the laser forming process. It was also decided to determine what influence the variation in power levels would have on the microstructure and the mechanical properties of titanium [8]. There is a widespread belief that a line energy threshold must be exceeded in order to commence with permanent deformation by the temperature gradient method (TGM) [9]. A line energy of 90 kJ/m was considered after unsuccessful attempts to bend samples at a power of 1.5 kW where the line energies of 35 and 47 kJ/m, respectively, were used. For powers ranging from 2.5 to 3.5 kW, the line energy was kept constant at 90 kJ/m, and the scanning velocities were adjusted to suit the required line energy, in this instance 90 kJ/m.

The prime pocket monitor shown in **Figure 2** was used in this study to measure the laser power projected on the surface of titanium specimens. Readings were taken to fully understand the incident power hitting the titanium plate surface. As an example for a laser power setting of 3500 W, the pocket monitor reader would show 3250 W. This value indicates a 10% loss in power on the irradiated sample [8]. This assisted in understanding and acknowledging the presence of losses in laser irradiation in material processing. For the purpose of this study, the losses were ignored and not taken into consideration in the analysis.

2.2 Mechanical forming

Metals are used extensively as engineering materials in part because of their ability to deform plastically. Various forming processes are used to form

Figure 2.
Prime pocket monitor.

engineering materials to desired shapes and sizes. These forming operations generally occur after the metal is cast, so it is important to understand how forming operations interact with pre-existing casting defects. Most metal forming operations reduce the severity of casting defects, such as microporosity, and break up coarse particles, such as non-metallic inclusions, that form during solidification. The mating die method was used to bend titanium alloy plates to the desired radius of curvature. The mating die method of stretch-draw forming involves an upper and lower die block mounted in a hydraulic press bed. The workpiece is securely held in tension by movable grippers. Yield stress of the finished part may be increased as much as 10% by the stretching and cold working operations. Shown in **Figure 3** is how the bending of titanium plates was achieved using the mechanical forming machine and also the resulting shape.

The objective of this study was to bend a flat plate of titanium to a radius of 120 mm, and this would help in understanding the principles behind the mechanical forming process. The study also aimed at comparing mechanical to laser forming with regard to the microstructure and mechanical properties of the material and any changes that happen thereafter as a result of both forming operations.

2.3 Tensile test

The mechanical properties of CP grade 2 titanium alloy vary with its grade as indicated in **Table 4**. CP grade 2 titanium plate specimens were evaluated according to the American Society for Testing and Materials (ASTM) E8/E8M test method. The tensile test was performed on the parent material (CP grade 2 titanium plates) in accordance with ASTM E8, using the Hounsfield machine.

The resulting data were made available using computer software of the machine. The table shows average values taken from both the transverse and longitudinal directions of the plate. The ultimate tensile strength (the maximum engineering stress in tension that may be sustained without fracture) is given as 452 MPa, the yield 338 MPa and a percentage elongation of 28%.

Figure 3.
Mechanical forming.

Alloy	E (GPa)	$\delta_{0.2}$ (MPa)	UTS (MPa)	Elongation (%)
Grade 1	105	170	240	24
Grade 2	105	275	345	20
Grade 2 (current study)	**105**	**338**	**452**	**28**
Grade 3	105	380	445	18
Grade 4	105	480	550	15

Table 4.
Mechanical properties of CP grade 2 titanium alloy.

2.4 Microstructure

Figure 4 shows microstructures from the parent material specimens, and this material has equiaxed α-grains usually developed by annealing cold-worked alloy above recrystallization temperature. The microstructure has shown results from the manufacturing process of CP grade 2 titanium, which cannot be altered in the plates without the addition of heat or cold deformation processes.

The microstructure of mechanically formed plates contains the same equiaxed alpha grains found in the parent material. Mechanical forming produces no heat, and therefore the similarities in microstructure are to be expected. There were no major changes to the microstructure as a result of this process when compared to the as received material [10]**.** The microstructure of a mechanically formed plate is shown in **Figure 5**.

Figure 6 shows the fine structure of titanium from the plates irradiated at a power of 1500 W using line energies of 35 and 47 kJ/m, respectively. There is a variation in the depth of the heat-affected zone (HAZ) for both line energies [10]. The unaffected material in both cases has equiaxed α-grains similar to those in the parent material. Based on microstructural observations, it becomes clear that the temperature generated at **35 kJ/m** was less than that generated at **47 kJ/m** as it could

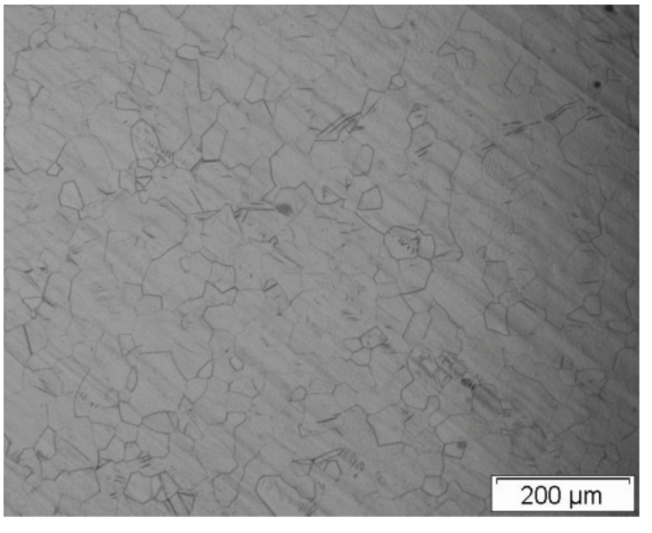

Figure 4.
As received material [parent material].

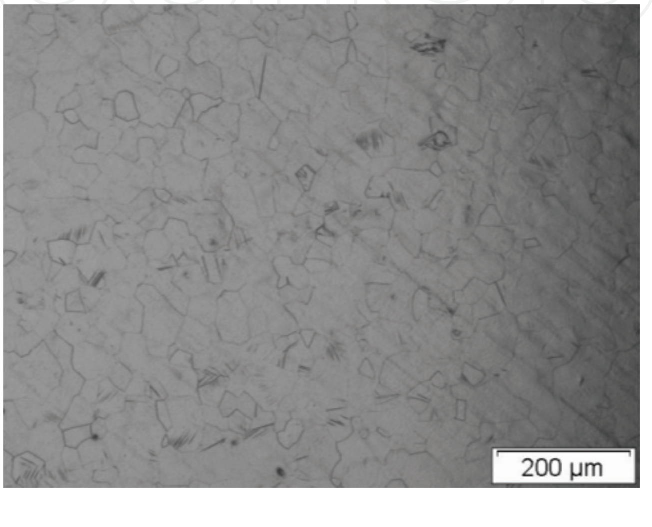

Figure 5.
Mechanically formed microstructure.

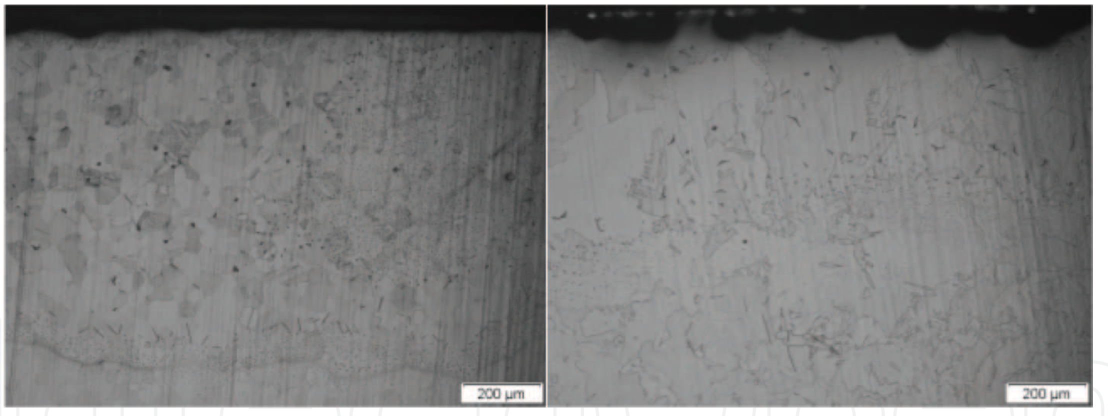

Figure 6.
Microstructure of laser formed plates [1.5 kW, 35 and 47 kJ/m].

not penetrate as deep to effect changes deeper in the microstructure away from the laser-irradiated surface.

The resulting microstructure from a line energy of 35 kJ/m points to a higher scanning velocity. The thermal energy from the laser managed to effect changes to a quarter of the plate's thickness [10]. The cycle took around 18 minutes to irradiate all the 10 plates in each batch at this power and line energy setting. The laser forming process resulted in a semi-circular-shaped heat-affected zone in the lower line energies (**35 and 47 kJ/m**). The area not affected by the heat in both cases shows smaller grains than those in the heat-affected zone. Grain size depends largely on temperature attained during the laser forming process, and grain growth proceeds more quickly as temperature increases. All the figures shown clearly reveal the influence of temperature on the microstructure, and the portion affected by laser energy has grains which are much bigger than those not affected by heat [10]. This is the reason why there is variation in the microstructures.

Figure 7 shows a major change in the microstructure of CP grade 2 titanium plates with enlarged primary α-grains and enlarged β-grains (**2.5 kW**). The structure consists of much bigger equiaxed alpha grains in the structure. The resulting microstructure is a result of thermal energy developed by the process parameters on the plates irradiated. Thermal energy is the main initiator in microstructural layout in all the laser formed plates. The microstructure managed to change only halfway through the plate which explains why there was minimal bending on the plates irradiated. Alpha titanium is cooling rate sensitive as seen by differences between the top section (laser-facing side) and the middle section. The microstructure

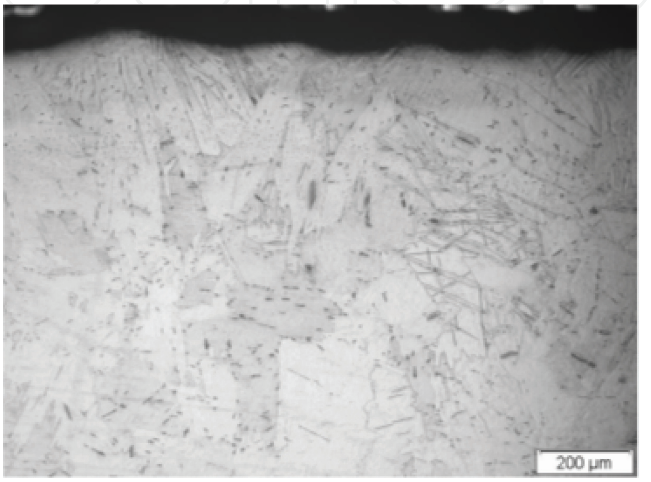

Figure 7.
Microstructure of a laser formed plate [2.5 kW, 90 kJ/m] [10].

formed as a result of the heat and cooling rate is not the same throughout the sample as witnessed on the as supplied parent plate. There are differences in microstructure between the top, the middle and bottom sections of the plate samples.

On the section of the plate closest to the source of laser irradiation and as thickness of the plate increases, the effect of thermal energy diminishes. The different microstructures shown are also an indication of different hardness values. The forming parameters at this power level led to plastic deformation on the laser-facing side. Before getting to plastic deformation, the grains were similar to those of the as received material (parent and mechanically formed plates). The scanning velocity used here happens to be the lowest in this study. The low scanning speed meant that the laser got more time to effect changes per unit area of the material resulting in the microstructure shown. The cooling of the plates also contributed to the microstructure. All the plates were naturally cooled. Thermal measurements have also shown the effect of the scanning velocity on the material. In multiple scan scenarios, each scan effects change on the microstructure. Differences in microstructure are brought about by the laser intensity power of **2.5 kW** which makes a significant change in the microstructural layout [10].

Figure 8 also shows the microstructure of a sample irradiated at **3 kW**, and with this plate an increase in power results in gradual change to the microstructure of titanium. The microstructure has much bigger equiaxed-α (alpha) and (beta) β-grains compared to a power of **2.5 kW** and the supplied parent material. The initial microstructure has an effect on the mechanical properties of titanium. During the process, changes in temperature affect the microstructure which in turn influences the mechanical properties of titanium. The changes in temperature and cooling rates also play a role in resulting mechanical properties. The high temperatures attained effected the top and bottom sections of the plates. An increase in power from 2500 to 3000 W meant that scanning speeds had to be adjusted in order to get to a line energy of 90 kJ/m. This reduced the time taken to irradiate the batch of samples. The heat flux increases by about 18% when the power is adjusted to 3000 W. There was also a reduction of 18% to the process time. The changes in heat flux indicate higher temperatures on the plate surface [10]. The alpha and beta grains are bigger closer to the centre of the irradiated plates and elongated closer to the laser-facing surface. The thermal energy generated resulted in different microstructures between the top and bottom halves of the sample. It should also be eminent that with an increase in power from 2.5 to 3 kW, there is a reduction in time taken to achieve irradiating the plate samples. The altering of power from 2.5 to 3 kW results in an 18% increase in the amount of heat flux generated and a 19%

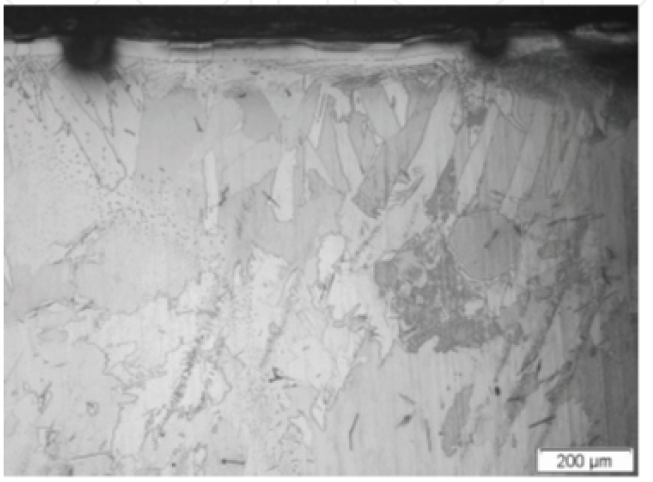

Figure 8.
Microstructure of a laser formed plate [3 kW, 90 kJ/m] [10].

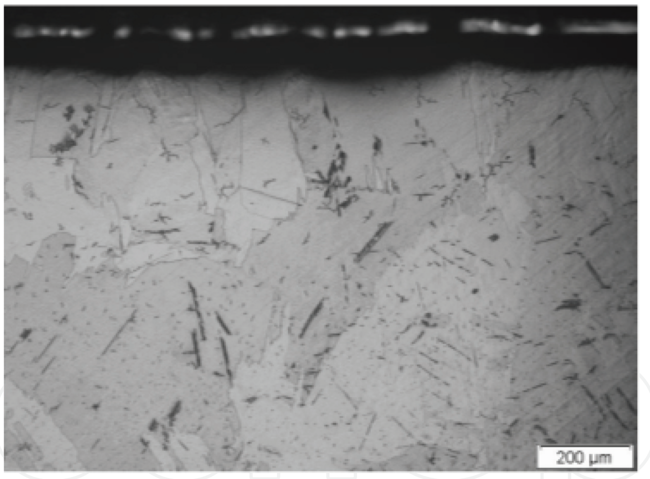

Figure 9.
Microstructure of a laser formed plate [3.5 kW, 90 kJ/m] taken from the top surface.

increase in scanning velocity. The change in scanning speed was done to achieve a line energy of **90 kJ/m** and resulted in the decline of process time by 18%. These numbers show that changes in the microstructure are to be expected as the new heat flux generated amounts to higher temperatures on the surface of the plate. In as much as cooling rates determine the resulting microstructure on titanium alloys, the processing temperatures also play an important role as well [10].

Figure 9 shows the microstructure layout as a result of laser forming at the highest power setting. The grains from this setting were the biggest in all the plates evaluated in this study. Twin bands can be seen throughout the microstructure of the plate. All sections of the plate had different grain sizes attesting to different cooling rates in the plate. The surface facing the laser did not cool down at the same time as the opposite side of the plate [10]. Acicular alpha can also be seen on the side opposite the laser-irradiated surface. The complete laser irradiation for these samples took about 20 minutes, which explains the changes in the microstructure when compared to a power of 2.5 and 3 kW, respectively. Changing the power from 2500 to 3000 W resulted in a 40% increase in heat flux. The heat flux increased by 16% from a power of 3000–3500 W. This means that by changing the power values, there was a related increase in the heat transferred per unit area, per unit time. These changes contributed to changes in the accompanying microstructure and mechanical properties. The study on the microstructure and mechanical properties helped in understanding the behaviour of titanium in different forming scenarios. The information gathered also made it easier to analyse the hardness results.

2.5 Hardness

The hardness number is a resistance for the local plastic deformation, and the hardness is closely related to residual stresses [9]. The average Vickers hardness obtained for the parent material is 160 $\pm$ 5Hv0.3, and whilst the average hardness number for the parent material is higher than that obtained in mechanically formed samples, the laser formed specimens show higher values. The average hardness results of the mechanically and laser formed CP grade 2 titanium specimens are shown in **Table 5**.

Mechanically formed plates did not behave like laser formed samples as there was a slight increase in hardness moving away from the top section resulting in an average hardness of 130 $\pm$ 5Hv0.3. This is a result of changes in the material structure caused by the die during mechanical forming. The microstructure of plates irradiated at **1.5 kW** (**35 kJ/m**) indicate that heat energy could only penetrate

Material	Parent (as supplied)	Mechanically formed	1.5 kW (35 kJ/m)	1.5 kW (47 kJ/m)	2.5 kW (90 kJ/m)	3 kW (90 kJ/m)	3.5 kW (90 kJ/m)
Average Vickers hardness	160	130	176	171	410	349	311

Table 5.
Hardness profile of laser and mechanically formed plate samples.

to a third of the depth of the sample (changing a small portion of the microstructure). Due to the low amount of heat generated, there was a minor change in the microstructure, and this translated to minimal changes in the hardness values. The increase in line energy from 35 to 47 kJ/m also contributed to an increase in hardness. The increase in hardness values could be traced back to the change in the size of the microstructure grains when compared with the parent material [10].

On examining the microstructure of specimen irradiated at **47 kJ/m** (1.5 kW), the change in the structure is more remarkable than the plate samples irradiated at **35 kJ/m** (1.5 kW). The processing speed at **47 kJ/m** was slower, making it possible for the laser to effect changes on the microstructure on a much improved scale resulting in a bigger heat-affected zone. Values obtained at this power level and line energy are higher than those obtained from a line energy of **35 kJ/m**. These values also show the importance of thermal energy in the laser forming process. The power of **2.5 kW** had the highest average hardness values in all the plate samples evaluated. This could be linked to the low scanning velocity at this power level. More heat was dissipated per unit area per unit time resulting in the high hardness values. Hardness values obtained at a power of 2500 W had high values than that of the parent material. Process parameters at this power level proved to be the optimum settings for this study. For those engineering applications in need of improved hardness properties on this grade of titanium, these settings could be used. The optimum settings resulted in the highest value of Vickers hardness in this study at 410Hv0.3. The hardness value obtained shows a 100% increase in hardness when compared to both the parent and mechanically formed plates [10].

The reduction in hardness values at this power setting could be traced back to the grain structure found in samples irradiated. The microstructure contained acicular alpha and beta phases which have a significant effect on the mechanical properties of titanium. An average Vickers hardness value of 349Hv0.3 was obtained at this power setting, and it was the lowest on the samples evaluated. Plates irradiated at 3000 W had the hardness value of 349Hv0.3 in plates formed at a line energy of 90 kJ/m. The same plates showed a marked improvement in hardness at the middle section of the plates. The forming process effected physical changes on the surface of the plates. These changes translated to changes in the hardness of the material. The results show an improvement of more than 100% when compared with the as received material. These changes also made the material hard to polish during the preparation of residual stress samples [10].

A hardness value of 311Hv0.3 was obtained at a power setting of 3500 W. This is the third highest value in samples irradiating a line energy of 90 kJ/m. The size of grains and their structure were different when compared to other laser formed plates. Readings taken from the top section of the laser-irradiated side indicate a considerable increase in the average hardness of titanium. An average Vickers hardness value of 311Hv0.3 was obtained from the top section which indicates a 40% increase in the hardness of titanium. The Vickers hardness readings taken closer to the surface show increased hardness values which are much higher than those obtained from the parent plate by a bigger margin. The improvement in hardness as a result of the laser forming process could help in the preparation of titanium for other engineering applications in need of hardened titanium plates [10].

2.6 Residual stress

The graphs plotted from the analysed plates were a result of residual stress information gathered by the MTS3000 machine on each plate sample evaluated. Comparisons are made between the plates based on the graphs obtained. The relieved strain from the parent material differs to that obtained from other evaluated plates. **Figure 10** shows relieved strain measured on the parent material, and all the micro-strain values (ε_1, ε_2, ε_3) show a slight reduction in strain as the depth of the hole increases.

The parent material shows minimum values in both residual stress and strain. Even when the drill depth increases, residual stress and strain remain constant. The graph obtained is totally different when compared to other plates evaluated in this study. With the other power levels in laser formed plates, there were changes in residual stress and strain with changes in drill depth [8]. This figure also shows an even distribution of residual strains on the material, and, unlike the laser formed plates, it seems possible that the temperature gradient on the parent plates during fabrication was not steep. The residual strains are not modified in any way but result from the manufacturing procedure used to produce titanium. The other forming operations witnessed in the study show a marked change to the residual stress/strain distribution. Residual stress from as received parent material shows steep residual stress versus drill depth gradient. The gradient is typical of stress induced by the manufacturing process. Surface residual stress is of high importance to mechanical design engineers as they show areas of high residual stress. The high residual stress areas help contribute to fatigue failure of the material [8]. All values obtained in the analysis of residual stress and strain of CP grade 2 titanium plates are shown in **Table 6**, and results obtained allude to the performance of these plates during fatigue testing.

The readings obtained from the parent material form the base for the analysis of residual stress, and strain results for the forming process utilised in this study. Results from the parent material show a difference between the maximum and minimum stresses of 12.9 MPa which is tensile. The stress values also give an indication as to why the parent material performed better than other plates during fatigue testing. The laser formed plates showed higher values of stress than both mechanically formed and the parent materials. The effect of these stresses is

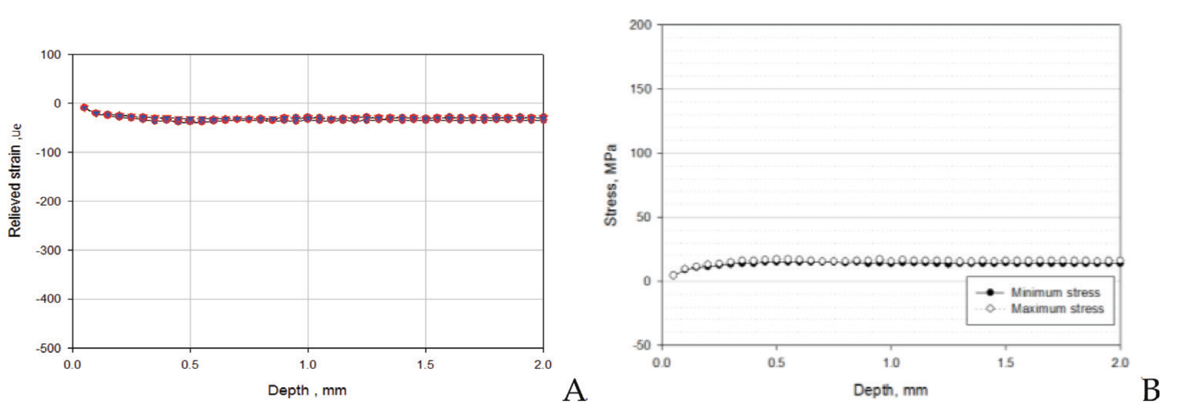

Figure 10.
Relieved strain (A) and stress (B) for parent material.

Samples	Minimum strain (με)			Maximum strain (με)			Minimum and maximum stress (MPa)	
	ε_1	ε_2	ε_3	ε_1	ε_2	ε_3	σ_1	σ_2
Parent material	−39,	−37	−32	−9.6	−9.81	−9	**4.1**	**17**
Mechanically formed	−111,	−59	−33	−16	−12	−4	**3.1**	**41.1**
1500 W (35 kJ/m)	−81	−180	−284	5	0.7	3	**−2.9**	**116**
1500 W (47 kJ/m)	−68	−245	−427	29	17	16	**−14**	**188.3**
2500 W	−199	−352	−443	−21	−27	−33	**11.4**	**181.8**
3000 W	−129	−276	−401	1.5	−5	−5.71	**−0.3**	**176.9**
3500 W	−166	−290	−403	−3	−2.61	−2.51	**1.4**	**181.9**

Table 6.
Residual stress and strain results [8].

therefore evident in fatigue testing and is documented in the results obtained [8]. The mechanical forming process resulted in minor changes to the relieved stress and strain, when compared to the parent material results. The mechanical forming process rearranges the residual stress and strain in the parent material. The term rearrange is applicable in this scenario as the material had residual stress within, prior to both forming processes. Some engineering applications encourage the presence of residual stresses within the material. The changes in residual stress are due to physical changes in the material as a result of laser and mechanical forming. Manufacturing processes introduce residual stress into mechanical parts, thereby influencing fatigue behaviour. The influence of all the forming operations is well documented in the analysis of fatigue results. The only difference between these processes is the intensity at which each forming process transpires. There are variations from process to process as witnessed in this study between mechanical and laser forming processes. After the attainment of maximum stress, there is a reduction in stress as the depth increases [8].

The mechanically formed plates had higher residual stress values than the parent material at 41 MPa. This is a 54% increase in stress when compared to the parent material. The difference in stress between maximum and minimum stresses was 38 MPa, a 66% improvement when compared to the parent material. These results had an influence on the fatigue results of the material. The graphs also show changes in residual stress with each forming process. There are similarities in residual stress between the parent material and the mechanically formed plates. The stress peaks at about 0.5 and 0.7 mm and then taper as maximum depth is approached. Based on results obtained from the parent material, forming moves the location of maximum and minimum principal stress closer to the surface. The low line energies had minimum effect on the residual stress distribution in the titanium plates [8] (**Figure 11**).

On the laser formed plates, there is a relative increase in the strain relaxation curve when compared to the parent and mechanically formed plates. In laser formed plates due to the physical changes in the material, there is a modification in the residual stress and strain due to phase transformation. The phase transformation is due to the intense heat from the laser and effects of the temperature gradient mechanism [8]. As witnessed on other laser formed plates, there is an increase in relieved strain as the line energy increases. The effect of deformation compatibility, as a result of internal stresses, is evident on the laser formed plates, and unlike mechanical forming, the effects of heat energy are evident on the tested specimens.

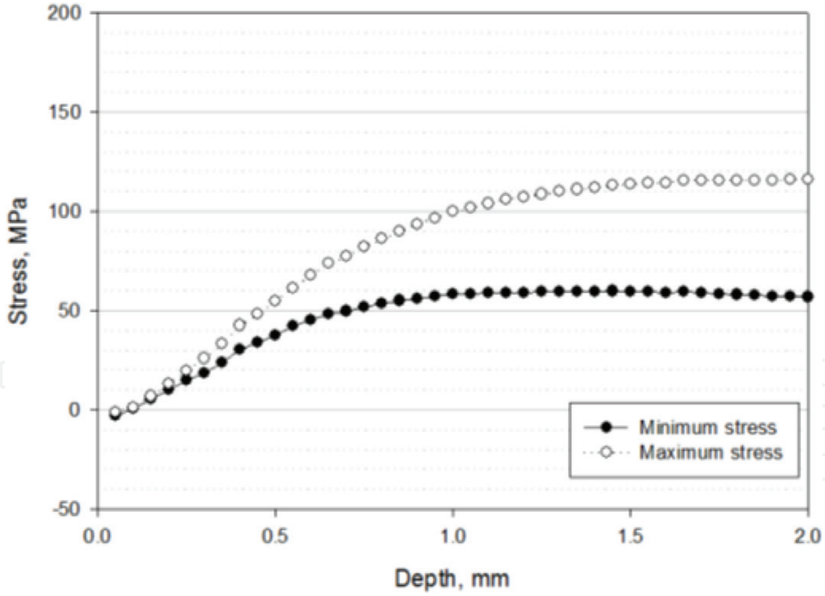

Figure 11.
Relieved stress, laser formed plates (1.5 kW, 35 kJ/m).

The laser forming process was carried out in such a way that there was an overlap on the scan tracks, meaning some portions of the laser-irradiated specimens did not get direct heat energy from the laser but were exposed to its effects. This resulted in large thermal gradients in the material contributing to an increased presence of internal stresses in the plates. The laser forming process has the ability to move the location of the maximum stress within the specimens as witnessed in all the laser formed specimens.

For the parent and mechanically formed specimens, the location of maximum principal stress was between 0.5 and 0.7 mm, respectively. With the laser formed plates, the location of maximum principal stress is between the depths of 1.5 and 2 mm. The changes in redistribution of residual stress are due to the thermo-mechanical properties of the laser forming process. For a power of 1500 W and a line energy of 35 kJ/m, the maximum stress attained was 116 MPa (T) and a minimum stress of 2.9 MPa(C). This maximum stress was the lowest in all laser formed plate samples. Maximum and minimum residual stress values do not decrease with changes in depth as witnessed with the parent plate. The changes in line energy change the location of maximum and minimum residual stress [8]. The line energy generated managed to penetrate and force a change on the microstructure of CP grade 2 titanium. Based on the microstructural analysis, there is a noticeable difference in microstructure between the line energies developed at a power of 1.5 kW (**35** and **47 kJ/m**).

The change in line energy from 35 to 47 kJ/m can be seen on the residual stress and strain results. With the line energy of 47 kJ/m, the relieved strain starts positive and ends negative due to a surge in gauge 2 and 3. These changes are due to the effects of laser forming which greatly influence the distribution of residual stress and strain. Changes in residual stress are also dependent on the process parameters and the line energy and heat flux generated. The line energy and heat flux are responsible for the phase transformation in the physical properties of the material. Titanium changes phase at a temperature of 883°C, and it appears that temperatures exceeding this value were reached during the laser forming process. The thermal gradient is the same as that obtained at an energy of 35 kJ/m. The same goes with values in heat flux which remain constant. The only difference is brought about by changes in scanning speed and beam interaction time. Changes in line energy caused variations in minimum and maximum residual stress values [8].

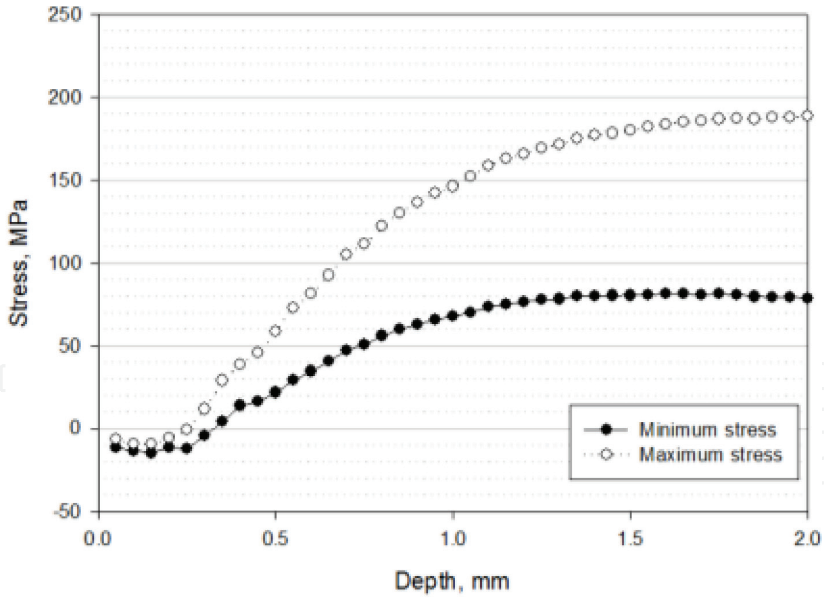

Figure 12.
Laser formed plates (1.5 kW, 47 kJ/m).

The maximum and minimum stress was the highest in all the specimens evaluated at 1.5 kW and is shown in **Figure 12** above. The increase in residual stress resulted in a reduction to fatigue life in laser formed specimens. There is a steady increase in both maximum and minimum principal residual stress and strain as line energy increase. These changes are influenced by changes in temperature which also affect the microstructure. Differences in residual stress are a result of different scanning speeds. The line energy of 47 kJ/m was obtained after adjusting the scanning velocity [from 2.6 to 1.9 m/min]. The change in speed meant there was an increase in beam interaction time causing more physical changes to the material. More time was therefore available per unit area per unit time to cause changes to the material. The power setting of 2500 W had a slower scanning velocity, a high heat flux, a higher line energy and minimal beam interaction time. These plates also experienced a higher thermal gradient which influenced changes in residual stress and strain [8].

Changes in microstructure also influenced the distribution of residual strains. The variations in thermal gradient between a power of 1500 and 3500 W caused major changes to the microstructure and led to a rise in non-uniform thermal strains, whose effect became hyperbolic when the material is elastically stiff and has a high-yield strength. The variations in temperature caused changes to the resulting mechanical properties. This means that the material properties are largely dependent on temperature. The higher the temperature, the greater will be the change in material properties [8].

The microstructure of the laser-irradiated specimens' changes as the depth of the specimen increases moving away from the laser-irradiated surface. The change in line energy to **90 kJ/m** resulted in an increase to the maximum principal stress which continued being in tension. Unlike the power of 1.5 kW, both maximum and minimum principal stresses start as being in tension and not compressive closer to the irradiated (laser-facing) side [8] (**Figure 13**).

On plates irradiated at 2500 W, the maximum and minimum residual stress was 182 MPa (T) and 11 MPa©, respectively. The difference in stress was 170 MPa, and the maximum stress is obtained at a depth of 1 mm. High residual stress had a negative effect during fatigue testing, as the material had deformed plastically. There is an alteration in the thermal gradient at this power, and the scanning

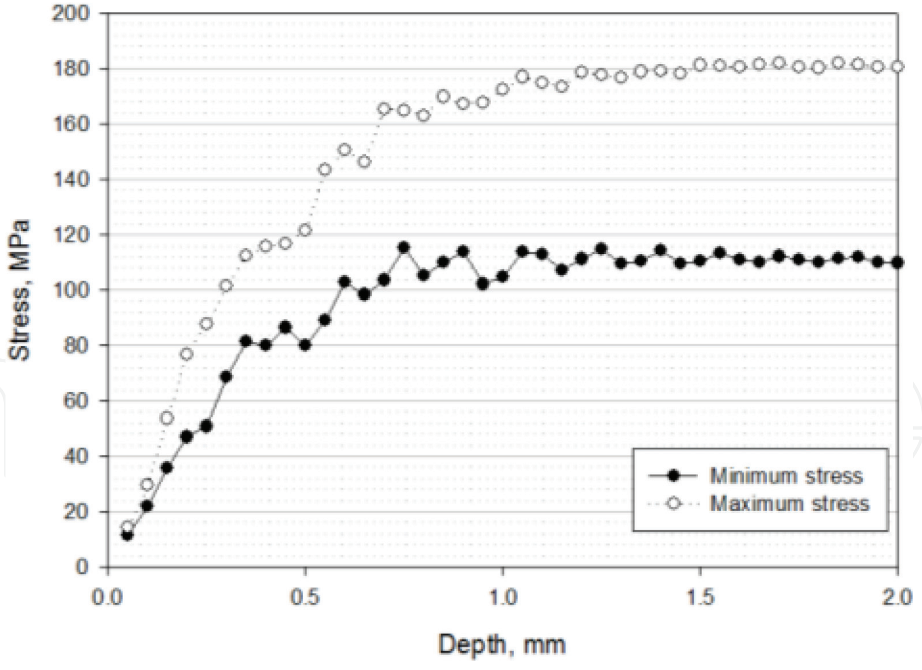

Figure 13.
Laser formed plates (2.5 kW, 90 kJ/m).

velocity is also the slowest in all the speeds used in this study. The slow scanning velocity led to variations in residual stress, when comparing plates irradiated at a power of 26,500 W. Changes in phases associated with the physical properties of the material are related to transformation strains. Strains can be viewed as modes of deformation with the special characteristics of being accompanied by a change in crystal structure [8]. All these factors influence residual stress distribution in titanium. At this power level, there is a reduction in both maximum and minimum stress values, which is in contradiction with other laser powers used in the study. This power had the optimum parameters for a line energy of 90 kJ/m [8] (**Figure 14**).

The specimens processed at 3 kW had a maximum stress of 176 MPa and a minimum stress of 0.3 MPa (C). The residual stresses had a major effect in fatigue

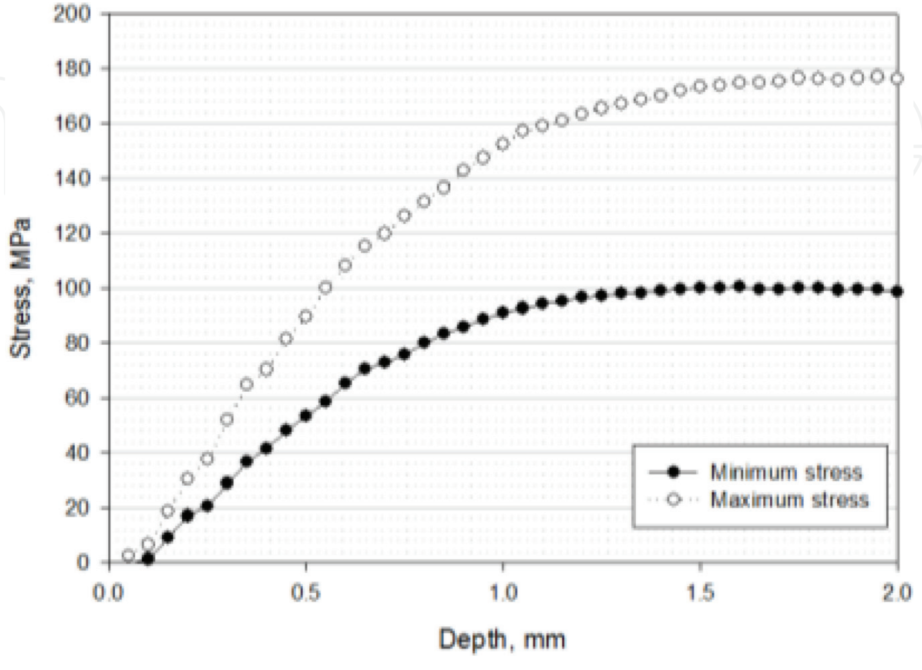

Figure 14.
Laser formed plates (3 kW, 90 kJ/m) [3].

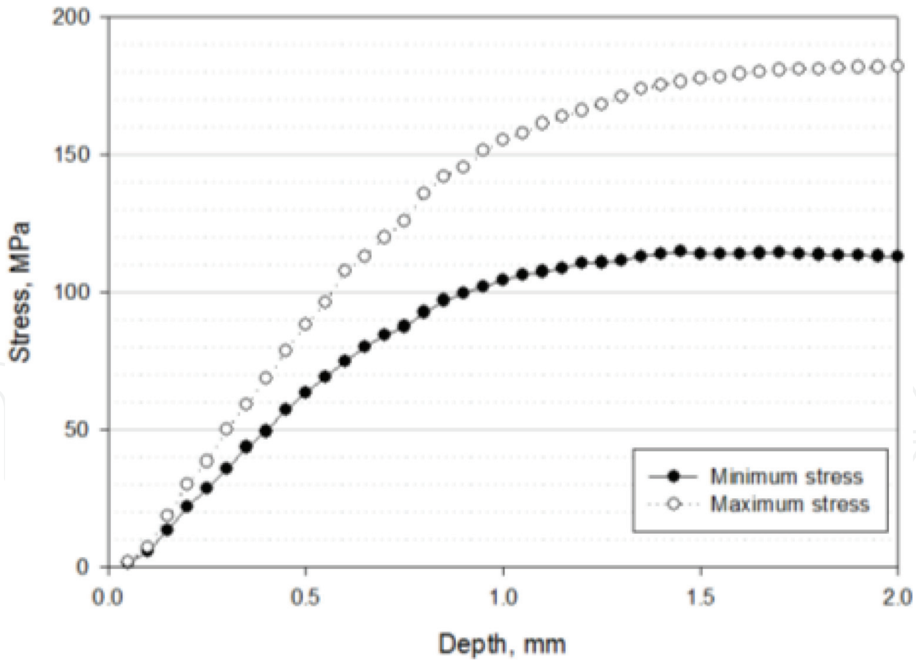

Figure 15.
Relieved stress (3.5 kW).

life as they changed the location of the fracture line. The maximum principal stress at a power of 3000 W is obtained at a depth of 2 mm. The changes in residual stress and strain are closer to the surface of the irradiated plate. The laser forming process increases the hardness of titanium. Residual stresses in this study are a result of interactions between time, temperature and the material. These factors played a major role in the resulting residual stress layout on all laser formed plates. The effect of the thermal gradient is evident when these plates are compared with plates not affected by thermal energy. The highest temperature gradient was obtained at a power of 3500 W. The thermal gradient became a deciding factor in microstructural layout. Even though the line energy was the same from a power of 2500 W up to a power of 3500 W, the effects on the microstructure were not uniform. This led to the conclusion that the thermal gradient is the most influential factor in laser forming [8] (**Figure 15**).

The maximum stress obtained at 3.5 kW was the second highest at 181.9 MPa (T) and a minimum stress of 1.4 MPa (T). The hardness of plates was equivalent to the parent material, but this is where similarities end. The difference in stress was 185 MPa on the laser-processed plates. This difference in stress is related to changes in hardness of titanium as a result of laser forming process. The differences in temperature between 3000 W and 3500 W played no role in influencing minimum and maximum residual stress. The optimum settings for a line energy of **90 kJ/m** are at a power of 2.5 kW [8].

3. Conclusions

The primary motivation of this study was to investigate, analyse, characterise and compare laser and mechanical forming processes. The study focussed on the main parameters that influence the bending of plates and their effect on the microstructure and mechanical properties. New theories and discoveries are discussed in the context of contribution to the subject and body of knowledge which is wide and immense in scope. Theories and conclusions are as follows:

The use of thinner gauge material: The study has come up with a new application for the laser formed titanium. Laser formed titanium plates become extremely hard and could be used in the defence industry for bullet-proof body vests and applied on armoured vehicles. Titanium is light in weight and coupled with a hardened surface resulting from laser forming could be a viable solution. Current armoured vehicles are heavy and slow due to the materials used, and venturing into materials like titanium could be a breakthrough to the defence industry. The laser forming process has the ability to customise the mechanical properties of any material, and therefore with this possibility thinner gauge material could be used for the benefit of this industry.

The control of the radius of curvature: Controlling the radius of curvature using the laser forming process is complex and results in uncontrollable bending of the material. Magee et al. saw a great potential for accuracy and controllability on the amount of forming with the laser, but the current study contradicts what he thought possible with the process. Titanium has proved its unpredictability in this study resulting in no proper control of the radius of curvature as envisaged.

The line energy: This is the fraction of the laser power and traverse speed. According to Magee there is a critical energy input below which no plastic straining occurring in each experiment. The study agrees with Magee on the fact that a higher line energy results in more pronounced bending of the material. Maintaining a constant line energy does not result in same bending of plate specimens from the irradiated batch of plates. An increase in laser power increases the line energy and thermal gradient which all determine the extent of bending in titanium. The use of higher line energies compromises fatigue properties of titanium as there is no proper control of temperature, and therefore precise thermo-mechanical control is needed for the success of this process.

The industrial use of laser forming: Contrary to what was envisaged on initiating this study, the laser forming process does not pose a challenge to current popular forming methods. At the moment the best process for forming is mechanical forming due to the ease with which any desired shape can be formed in minimal time. Laser forming is much slower than mechanical forming, and changes brought by the laser forming process could be undesirable to other industrial applications.

The thermal gradient: The low thermal conductivity of titanium means higher thermal gradients are needed for pronounced bending of CP grade 2 titanium. Higher thermal gradients result in higher residual stresses in the material and a complete change in the physical properties of the material. Changes in physical properties could be desirable or less desirable depending on industrial application.

Surface hardening: The laser forming process resulted in surface hardening of CP grade 2 titanium plates. This had a negative effect on the fatigue life of specimens, as there was a reduction in fatigue life. This is contrary to the findings by Konstantino and Altus [11] who reported improvements in fatigue life of Ti-6Al-4 V which behaves in the same manner as CP grade 2 titanium plates. The improvement in fatigue life was achieved by laser heating based on reduced fraction of α (alpha) in the microstructure and a reduction in grain size. In this study there was an increase in grain size as a result of laser heating which completely changed the granular structure of the material. A significant microstructural refinement was observed during this study resulting in the formation of α-martensite. Hardness values are dependent on the line energy generated during the laser forming of titanium. The higher the line energy, the higher will the hardness be for CP grade 2 titanium plates. The laser-irradiated surface hardens as a result of the laser forming process making it difficult to polish and prepare plates for residual stress measurements. In laser formed CP grade 2 titanium plates, the hardness changes with specimen depth as a result of the effects of thermal energy from the laser, which is the heat source.

The residual stress: In all the forming processes analysed, changes in residual stress are greatly influenced by process specifications. In laser forming however these changes are dependent on the process parameters used, as these differ with each laser power. Thermal gradient influences the development of residual stresses. In mechanical forming changes in residual stress are determined by the complexity of the formed shape. It was envisaged at the beginning of the study that residual stress would be enhanced but the laser forming process made undesirable changes to the underlying residual stress distribution. According to Norton [5] good design requires that an engineer try to tailor the residual stresses to a minimum, not create negative effects on the strength and preferably to create positive effects. Fatigue failure is a tensile residual stress phenomenon. The laser forming process resulted in increased tensile residual stress in the specimens due to higher line energies. The use of lower line energies on CP grade 2 titanium results in no bending of the material, and therefore high tensile residual stress remains part of the process if there is forming to be done. The parent material and mechanically formed plates had low residual stress values which was an advantage during fatigue testing as these had a higher fatigue life.

Microstructure: The mechanical forming process has a minimal influence on the microstructure of CP grade 2 titanium plate specimens compared to the effects of laser forming. The laser forming process results in changes in grain size as thermal energy is increased. Changes in the microstructure influenced the mechanical properties of CP grade 2 titanium plates.

Beam interaction time: The beam interaction time is significant in the analysis of resulting mechanical properties as a result of the laser forming process. The time taken to heat up an area influences the mechanical properties and the microstructure of plate samples.

Heat flux: The heat flux is significant in changes observed with titanium plates, and each laser power setting evaluated had a different reading, resulting in varying microstructures on the plates evaluated. The depth of laser penetration depends on the amount of line energy generated.

Laser power: An increase in laser power leads to the oxidation of the passive layer on CP grade 2 titanium plates as a result of the concentrated thermal energy generated by the laser.

Forming parameters: The changing of forming parameters in the laser forming of CP grade 2 titanium succeeded in obtaining optimum operating parameters (in the case of this research, a power of 2.5 kW, a line energy of **90 kJ/m** and a scanning velocity of 1.67 m/min) for titanium.

Plates: Laser formed titanium plates should not be used in applications requiring prolonged fatigue life. The process is only beneficial in applications where hardness is a priority without a need for high fatigue life, and perhaps the process could be beneficial in military defence applications. Laser formed titanium plates do not bend to the same radius of curvature as proved in this study.

Process control: The process needs precision control of processing parameters as they play a major role in the final microstructural layout and mechanical properties. For good fatigue properties, thermo-mechanical/laser processing of titanium needs to be conducted using lower line energies but then these do not bend the material.

Acknowledgements

Nelson Mandela University (NMMU) for financial assistance and laboratory facilities. Mr. Victor Ngea-Njoume for technical assistance.

Author details

Kadephi Vuyolwethu Mjali[1*] and Annelize Botes[2,3]

1 iThemba LABS—Laboratory for Accelerator Based Sciences, Somerset West, Cape Town, South Africa

2 Council for Scientific and Industrial Research (CSIR), Pretoria, South Africa

3 Department of Mechanical Engineering, Nelson Mandela University, Port Elizabeth, South Africa

*Address all correspondence to: vuyo.mjali@gmail.com

References

[1] Rosi FD, Dube CA, Alexander BH. Mechanisms of plastic flow in titanium-determination of slip and twinning elements. Transactions of AIME. 1953; **197**:257-265

[2] Smith WF. Structure and Properties of Engineering Alloys. 2nd Edition. McGraw-Hill Science/Engineering/Math; January 1 1993. ISBN-13: 978-0070591721

[3] Lawrence J. Advances in Laser Materials Processing. Technology, Research and Applications. 2nd Edition. Woodhead Publishing; ISBN: 9780081012529

[4] Edwardson SP, Watkins KG, Dearden G, French P. Strain Gauge analysis of laser forming. Journal of Laser Applications. 2003;**15**:225. https://doi.org/10.2351/1.1620000

[5] Norton RL. Machine Design-An Integrated Approach. 3rd Edition. Prentice Hall; 2005. ISBN 10: 0131481908/ISBN 13: 9780131481909

[6] Ion JC. Laser processing of engineering materials. Principles, Procedure and Industrial Application. 1st Edition. Butterworth-Heinemann; 2005. ISBN: 978-0-7506-6079-2

[7] Magee J, Watkins KG, Steen WM, Calder N, Sidhu J, Kirby J. Laser forming of high strength alloys. Journal of Laser Applications. 1998;**10**(4):149-155

[8] Mjali KV, Els-Botes A, Mashinini PM. Residual Stress Distribution and the concept of total fatigue stress in laser and mechanically formed commercially pure grade 2 titanium alloy plates ASME 2017 12th International Manufacturing Science and Engineering Conference collocated with the JSME/ASME 2017 6th International Conference on Materials and Processing Volume 2: Additive Manufacturing; Materials. Los Angeles, California, USA, June 4-8, 2017. Conference Sponsors: Manufacturing Engineering Division. ISBN: 978-0-7918-5073-2

[9] Knupfer SM, Moore AJ. The effects of laser forming on the mechanical and metallurgical properties of low carbon and aluminium alloy samples. Materials Science and Engineering A. 25 June 2010;**527**(16-17):4347-4359

[10] Mjali KV, Els-Botes A, Mashinini PM. The Effects of Laser and Mechanical Forming on the hardness and microstructural layout of commercially pure grade 2 titanium alloy plates. ASME 2017 12th International Manufacturing Science and Engineering Conference collocated with the JSME/ASME 2017 6th International Conference on Materials and Processing Volume 2: Additive Manufacturing; Materials. Los Angeles, California, USA, June 4–8, 2017. Conference Sponsors: Manufacturing Engineering Division. ISBN: 978-0-7918-5073-2

[11] Konstantino E, Altus E. Fatigue life enhancement by laser surface treatment. Surface Engineering. 1999; **15**(2):1-3