Experimental Investigation of Laser beam forming of Titanium and Statistical Analysis of the Effects of Parameters on Curvature

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***Abstract*—** Laser beam forming, a non-contact manufacturing process has become a viable manufacturing process for shaping metallic components. The capability of laser beam forming and bending demands more experimental studies to identify an optimized parameter setting and the likely parameters influencing the formed curvature. This paper investigates experimental laser beam forming of Ti6Al4V titanium alloy using a 4.4 kW Nd: YAG laser and studied the effects of the process parameters on the formed curvature. It was established that an increase in both the laser beam power and the number of scan tracks reduces the radius of curvature in the formed sheets having a more dome shape. The scan speed on the other hand, achieved the same good curvature at a slower or reduced scan speed to allow enough laser – material interaction. Furthermore, both the ANOVA and the regression analysis confirmed the repeatability of the experimental data. A simple regression model was developed based on the known active parameters to determine approximate curvatures instead of running a series of experiments.

***Keywords*—** Laser beam forming, Taguchi Orthogonal array,

I. INTRODUCTION

LASER Beam Forming (LBF) is a unique technique that is used to deform plates and sheets made of metal materials such as stainless steel, mild steel, light alloys of aluminium, magnesium and titanium. Most of these metals and alloys have high thermal expansion coefficient. Laser beam forming with thermal stresses has been known for several years and is gradually coming out of the developmental stage [1–7]. Mostly, the attention on laser beam forming has been focused on laser forming along linear irradiation paths, and the sheets employed in the laser beam forming process were mainly those of materials with good deformability at the ambient temperature, such as steel, titanium, aluminium etc. This process has now gained significance in the last decade in several field of industrial manufacturing. During the process of laser beam forming, the deformation is induced in a controlled manner in plates and sheet by tracking the laser beam across one side of the material. Consequently, temperature gradients are developed through the material thickness; this induces stresses because of the different expansion of adjacent layers that are at different temperatures [8]. The result of this phenomenon is the plastic deformation of the sheet metal. The heated zone of the underneath surface, which is not directly in contact with the laser beam is under the compressive stress and plastic strain. This results because of the restriction on the elastic part of the material. When the laser beam irradiation is completed, the heated zone is exposed to cooling and shrinkage which consequently induces some deformation following the pattern of the scan irradiation bringing about the curvature in the direction of the laser beam [9-12]. A schematic diagram of the laser beam forming process is shown in Figure 1.

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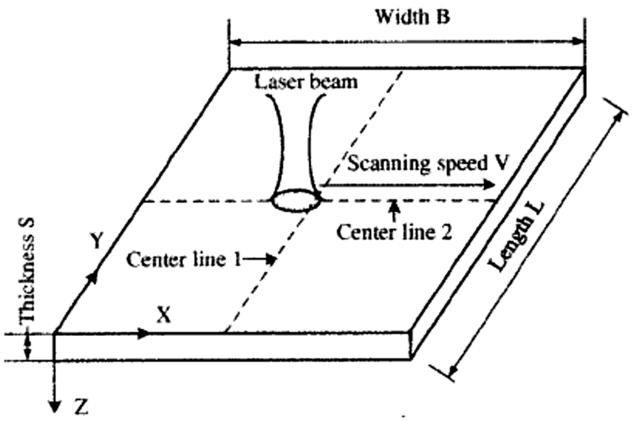

Figure 1 Schematic diagram of the LBF Process [13]

One of the main advantages of the laser forming process is that it does not require hard tooling or external forces. Hence, a laser forming process has many advantages, such as no springback, high process flexibility, production of complex shapes and the formation of very small parts. It also has a great potential for rapid prototyping and alignment procedures [14]. Typical applications are in the adjustment of welded construction joints, the bending of prototypes and small series production. It allows high automated manufacturing processes to occur and to reduce tooling costs for rapid prototyping. The process offers a great flexibility as a lot of other applications (such as soldering, brazing, welding, cladding and hardening) can be performed by means of the same equipment with a little modification of the experimental set up. The number of industrial applications of laser beam forming is continuously increasing, due to the possibility of forming highly reproducible accurate sheet metal products in a cost effective way [15-16]. Literature documented that laser beam forming started in the last two decades. One of the earliest studies on laser beam forming was credited to Namba (17-18) in 1985. The first industrial applications of laser beam were first studied by Scully [19] and Masubuchi [20]. Both studies were investigated for the forming of steel plates into three dimensional shapes employed for construction in ship yard. The ability to bend sheet metal both toward and away from the beam was reported. Frackiewicz [21] introduced rapid cooling of the sheet metal surface with a suitable liquid immediately after heating the surface with a laser. Geiger *et al*., [22] have suggested using the laser forming for straightening distorted car body shells after welding.

Several general comments can be made with respect to laser beam forming research to date [23–27]. In all of these past research investigations, most of the material of interest was mainly different grades of steels. This study will compliment the few published work on the laser beam forming of titanium and titanium alloys but most importantly reports on the formation of curvatures in the formed plates and not just straight bend angles as been widely reported. Hence, it is important to emphasise that work on laser beam forming of titanium and its alloys to different curvatures and the influence of the process parameters on the resulting curvatures are limited. As such, this study experimentally investigates the laser beam forming of Ti 6Al4V titanium alloy and statistically analysed the effects of the process parameters on the resulting curvatures.

II. Titanium and its alloy

Titanium is known to be the fourth abundant metal on the earth crust after aluminium, iron and magnesium. It has never been found as a pure metal but as an oxide i.e. $FeTiO_3$ (ilmenite) and TiO_2 (rutile). Titanium alloys are metals containing a mixture of titanium and other chemical elements, such alloys have excellent tensile strength and toughness even at extreme high temperatures. They are light weight metal with extraordinary corrosion resistance and ability to withstand high temperatures. It is known to have similar strength as steel but 45% lighter than steel, similarly, it is twice as strong as aluminium but only 60% heavier than aluminium [28]. Titanium alloys are generally classified into four major categories i.e. Alpha alloys, Near-alpha alloys, Alpha and Beta alloys and beta Alloys. Alpha alloys are a non heat treatable alloy and contain neutral alloying elements such as tin and alpha stabilizing element such as aluminium. It is stronger but with less ductile while Near-alpha alloys are alloyed with small percentage (1-2%) of beta phase stabilizers such as molybdenum, silicon and vanadium. On the other hand, Alpha & Beta alloys are metastable in nature and generally include some combination of both alpha and beta stabilizers which can be heat treated. The mechanical properties lies between that of the Alpha and beta phase titanium. Beta alloys are fully metastable alloy and contain sufficient beta stabilizers such as molybdenum, silicon and vanadium, this allow them to maintain the beta phase when quenched. The strength of Beta alloys can also be improved through being solution treated and ageing. Beta phase titanium alloys are also ductile compared to others [28–29].

The excellent properties of titanium have made it very suitable for applications mainly in the aerospace, marine, chemical, biomedical and sports. Some of the properties which include corrosion resistance of titanium have made it found application in propeller shafts, rigging tools and other boats components that are exposed to sea water. Good strength, low weight and resistance to high temperature also made Titanium very useful in airplanes, missiles, and rockets. Furthermore, its ability not to react with human body made titanium and its alloys to be a perfect metal to be used to create artificial hips, pins for setting bones and for other biological implants.

Titanium and its alloys have been further categorised into grades based on its unique properties and applications for the purpose of standardization according to ASTM. According to ASTM standards, there are over thirty different grades of Titanium alloys but Titanium grade 5 is considered for the purpose of this investigation. Grade 5 Titanium alloy is also known as Ti6Al4V, Ti-6Al-4V or Ti 6-4. It is the alpha-beta alloy, the most commonly used alloy because of its unique properties and ruggedness. In fact, it is regarded as the workhorse alloy of the titanium industry. It has a chemical composition of 6% aluminium, 4% vanadium, 0.25% iron (maximum), 0.2% Oxygen (maximum) and the rest Titanium. Titanium grade 5 is significantly stronger than commercially pure titanium while having the same stiffness and thermal properties, but with thermal conductivity of 60% lower in grade 5 titanium than commercially pure titanium. Among other properties, grade 5 titanium is treatable, excellent combination strength, corrosion resistance, weldability, formability and fabricability. Its unique properties made its applications span across both the aerospace airframe and engine components and non aerospace applications such as in the marine, offshore, turbine blades, vessels, and biomedical implants [28–29].

III. Experimental procedure

The samples were made from grade 5 titanium alloy sheets (Ti6Al4V), with sample size of 90 x 30 x 1 mm^3. Twenty seven different samples were laser formed and repeated with two replicates, this is to establish the repeatability of the experiment. The laser beam forming of the Ti6Al4V samples were carried out at the National Laser Centre - Council for Science and Industrial Research (CSIR-NLC), Pretoria, South Africa, using a kuka robot carrying the 4.4 kW Diode-Pumped Nd: YAG laser (ROFIN DY 027 – 044). The experiments were conducted with three different laser powers; scan speed and number of scan irradiation while the beam spot size and cooling flow rate were kept at 12 mm and 15 litres per minute respectively throughout the experiment. An open fixture was employed for holding the Ti6Al4V samples; this also allowed full deformation during the laser beam forming process. Pure argon gas was employed for shrouding the irradiated path to avoid oxidation and cooling the irradiated surface. The generated curvatures were measured using a coordinate measuring machine at three different locations on the curvatures and their average recorded. The experimental set up is shown in Figure 2.

Figure 2: Experimental setup for LBF of Ti6Al4V

After the forming process, the formed samples were sectioned, ground and polished according to the ASTM standard for metallographic sample preparation of Titanium. Shown in Figure 3 is the micrograph of the parent material.

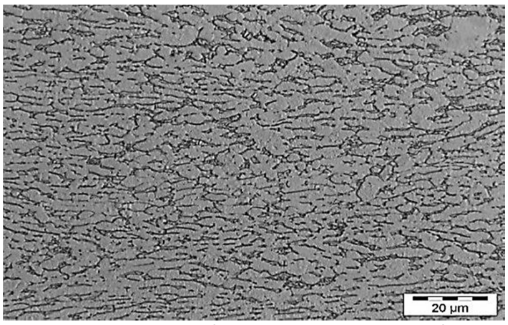

Figure 3: Micrograph of the parent material of Ti6Al4V

It was observed that the microstructure of the parent material (Figure 3) is characterized by lamellar structure of alpha and beta phases. The lighter phase is the alpha while the darker phase is the beta

IV. DATA ANALYSIS OF THE CURVATURE DATA

Many are the influencing processing parameters during the laser beam forming process but for the purpose of this study the following process parameters were considered; viz: the laser power, the laser spot size, the scan speed, the number of scan irradiation and the cooling flow rate. During this study, five parameters were considered at three different levels. Presented in Table 1 are the summary of all the process parameters considered.

Table 1: Summary of parameters at three different levels

	Levels		
Parameters	**1**	**2**	**3**
Laser Power, P (W)	600	800	1000
Laser spot size, B (mm)	12	12	12
Scan Speed, V (mm/s)	0.03	0.05	0.07
Number of Tracks, N	3	5	7
Cooling Rate, C (l/min)	15	15	15

The output of the process is determined by running tests at various levels of these parameters. It is believed that all these parameters influence the output directly or indirectly. Hence, the objective of this paper to determine the effect of the laser beam forming process on the developed curvatures. The curvature data are presented in Table 2. The curvature data generated was first validated using the regression analytical tool to establish the percentage error between the actual curvatures and that predicted using the regression analysis. The correlation between the parameters and the curvatures were analysed using the Analysis of Variance (ANOVA) and regression analysis.

4.1 Repeatability of curvature data

The curvature data generated during the laser beam forming of Ti6Al4V is presented in Table 2 and the data were validated for the average curvature data using regression analysis, this is presented in Table 3. The percentage error between the actual experimental data and the predicted was reasonable except for two data that were out of range. The physical examinations of the samples of these two data are fine and as such microstructural analysis and mechanical testing would be conducted to further establish the validity of these data. A best line of fit between the actual experimental values of curvatures and predicted values curvature were developed with an R-square value of 0.946, this is close to 1 as such the data can be relied upon. The line of best fit is shown in Figure 4.

Table 2: Detailed parameter array

S/N	P	B	V	N	C	Replicates of Curvatures		Average Values
1	1	1	1	1	3	P1-R1	P1-R2	292.84
2	1	1	1	2	3	P2-R1	P2-R2	185.86
3	1	1	1	3	3	P3-R1	P3-R2	112.71
4	2	1	1	1	3	P4-R1	P4-R2	242.45
5	2	1	1	2	3	P5-R1	P5-R2	132.90
6	2	1	1	3	3	P6-R1	P6-R2	41.24
7	3	1	1	1	3	P7-R1	P7-R2	211.07
8	3	1	1	2	3	P8-R1	P8-R2	101.63
9	3	1	1	3	3	P9-R1	P9-R2	56.72
10	1	1	2	1	3	P10-R1	P10-R2	448.83
11	1	1	2	2	3	P11-R1	P11-R2	291.34
12	1	1	2	3	3	P12-R1	P12-R2	170.87
13	2	1	2	1	3	P13-R1	P13-R2	344.56
14	2	1	2	2	3	P14-R1	P14-R2	210.82
15	2	1	2	3	3	P15-R1	P15-R2	93.03
16	3	1	2	1	3	P16-R1	P16-R2	275.21
17	3	1	2	2	3	P17-R1	P17-R2	142.56
18	3	1	2	3	3	P18-R1	P18-R2	23.85
19	1	1	3	1	3	P19-R1	P19-R2	503.45
20	1	1	3	2	3	P20-R1	P20-R2	377.81
21	1	1	3	3	3	P21-R1	P21-R2	186.47
22	2	1	3	1	3	P22-R1	P22-R2	400.52
23	2	1	3	2	3	P23-R1	P23-R2	251.24
24	2	1	3	3	3	P24-R1	P24-R2	135.87
25	3	1	3	3	3	P25-R1	P25-R2	300.00
26	3	1	3	5	3	P26-R1	P26-R2	196.29
27	3	1	3	7	3	P27-R1	P27-R2	91.15

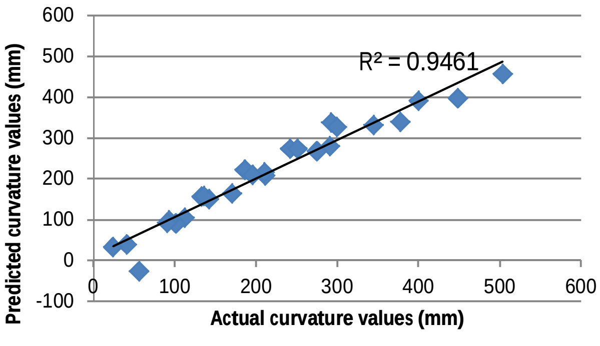

Figure 4: Line of best fit between actual and predicted values

Table 3: Average curvature validated data.

S/N	P	B	V	N	C	Average Values	Predicted Values	% Error
1	1	1	1	1	3	292.84	338.57	-15.61
2	1	1	1	2	3	185.86	221.51	-19.18
3	1	1	1	3	3	112.71	104.45	7.32
4	2	1	1	1	3	242.45	273.47	-12.80
5	2	1	1	2	3	132.90	156.42	-17.70
6	2	1	1	3	3	41.24	39.36	4.56
7	3	1	1	1	3	211.07	208.38	1.28
8	3	1	1	2	3	101.63	91.32	10.14
9	3	1	1	3	3	56.72	-25.74	145.37
10	1	1	2	1	3	448.83	397.75	11.38
11	1	1	2	2	3	291.34	280.70	3.65
12	1	1	2	3	3	170.87	163.64	4.23
13	2	1	2	1	3	344.56	332.66	3.45
14	2	1	2	2	3	210.82	215.60	-2.27
15	2	1	2	3	3	93.03	98.55	-5.93
16	3	1	2	1	3	275.21	267.57	2.78
17	3	1	2	2	3	142.56	150.51	-5.58
18	3	1	2	3	3	23.85	33.45	-40.26
19	1	1	3	1	3	503.45	456.94	9.24
20	1	1	3	2	3	377.81	339.88	10.04
21	1	1	3	3	3	186.47	222.83	-19.50
22	2	1	3	1	3	400.52	391.85	2.17
23	2	1	3	2	3	251.24	274.79	-9.38
24	2	1	3	3	3	135.87	157.73	-16.09
25	3	1	3	3	3	300.00	326.75	-8.92
26	3	1	3	5	3	196.29	209.70	-6.83
27	3	1	3	7	3	91.15	92.64	-1.63

4.2 Parameter effect on the curvature

The active parameters considered are the laser power, the scan speed and the number of scan tracks and those kept constant were the spot size and the cool flow rate. The main effect plot of the parameters on the average curvatures is shown in Figure 5(a) - (c), this can be used to draw preliminary conclusions on the effects of the parameters. It can be observed from Figure 5 (a) and (c) that an inverse relationship exists between the measured curvature, the laser power and the number of scan tracks. This implies that as the laser power and the number of scan tracks increases, the radius of curvature becomes smaller, having the two ends of the plate more closely. This further confirms that the laser power and the number of scan tracks have positively deformed the Titanium plate. On the other hand, it is observed in Figure 5 (c) that the radius of curvature developed becomes smaller as the scan speed increases. This phenomenon may be attributed to the lack of enough laser-

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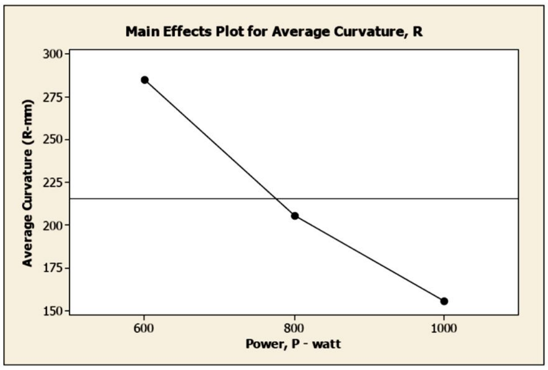
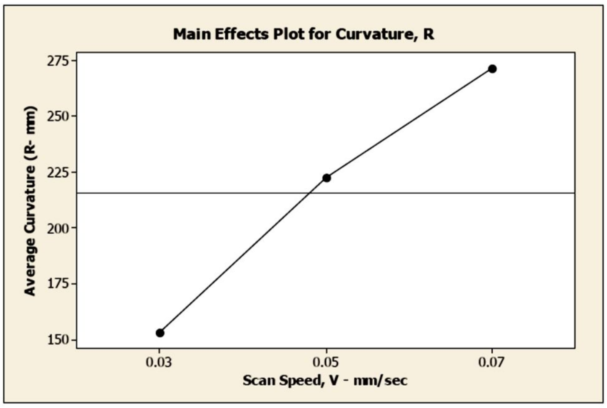
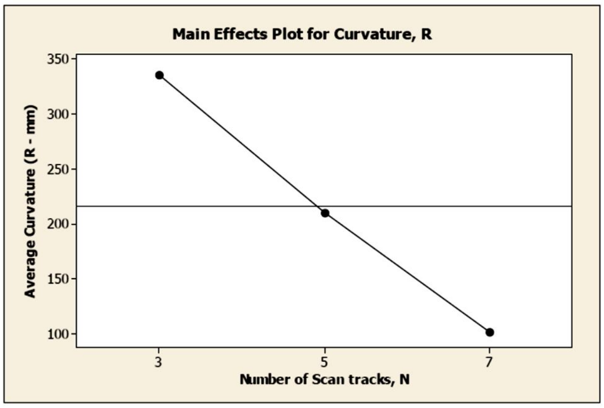
material interaction because the faster the laser beam across the sample, the little or minimal effects of the laser beam on the material.



(a)



(b)



(c)

Figure 5 (a) – (c): Main effect plots of R and parameters

4.3 Regression Analysis

The regression analysis was performed to establish the likely relationship that existed between the parameters and the curvature. A regression equation in terms of factor shown in Table 1 is obtained. The equation derived is a simple linear equation presented by equation 1.

The Regression Equation for the Curvature, R is given by equation (1)

$$R = 621 - 0.325P + 2959V - 58.5N \;------(1)$$

Where R is the radius of curvature (mm), P is the laser power (W), V is the scan speed and N is the number of scan tracks.

Table 4: ANOVA for curvatures

Predictor	Coef	SE Coef	T	P
Constant	620.65	39.35	15.77	0.000
P	-0.32547	0.03643	-8.93	0.000
V	2959.4	364.3	8.12	0.000
N	-58.528	3.643	-16.07	0.000

Table 4 presents the ANOVA Table of regression analysis. This Table indicates that the model estimated by the regression procedure is significant because the p-value is less than 0.005. In this study, 95% is chosen as the Confidence level; as such the p-values which are less than 0.05 indicate that the effect of the respective factors is significant. The ANOVA results can be therefore be trusted as listed in Table 4. In this Table DF is the Degree of Freedom, SS is the sequential sum, MS mean squares, F is the F-value and P is the P-value. The Analysis of Variance (ANOVA) used in evaluating the main effects of parameters on the process finds the significant factor effect based on the desired confidence interval. The following are assumed for the ANOVA analysis;

- Residual are normally distributed.
- Error is independent.
- Variance is constant.

Table 5: Analysis of Variance

Analysis of Variance					
Source	DF	SS	MS	F	P
Regression	3	385967	128656	134.67	0.000
Residual Error	23	21973	955		
Total	26	407941			

V. CONCLUSION

The Ti6Al4V titanium alloy sheets were successfully laser formed using a 4.4 kW Nd: YAG laser and the influencing processing parameters were studied. The active parameters investigated were the laser power, the scan speed and the number of scan tracks while the laser spot size and the cool flow rate were fixed throughout the experiments. The micrograph of the parent material consists of two phases, the

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Intergranular beta phase that is grayish in a matrix of light alpha phase. The experimental data were validated and the percentage error was within the acceptable values. A line of best fit also confirmed this claim with an R-square value of 0.946; this is close to 1 and as such can be accepted. The Analysis of Variance (ANOVA) was also conducted on the experimental data. The analysis from the main effect plots showed that an increase in the laser power and number of scan tracks also increases the radius of curvature developed while an increase in the scan speed reduces the radius of the curvature developed. In essence, all the three process parameters strongly influence the curvature developed in the formed sheets. Similarly, a regression model was developed for the curvature, R. With laser power, scan speed and number of scan tracts known, an approximate curvature can be developed.

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