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Laser Beam Forming of 3 mm Steel Plate and the Evolving Properties

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***Abstract*—**This paper reports the evolving properties of a 3 mm low carbon steel plate after Laser Beam Forming process (LBF). To achieve this objective, the chemical analyses of the as received material and the formed components were carried out and compared; thereafter both were characterized through microhardness profiling, microstructural evaluation and tensile testing. The chemical analyses showed an increase in the elemental concentration of the formed component when compared to the as received material; this can be attributed to the enhancement property of the LBF process. The Ultimate Tensile Strength (UTS) and the Vickers microhardness of the formed component shows an increase when compared to the as received material, this was attributed to strain hardening and grain refinement brought about by the LBF process. The microstructure of the as received steel consists of equiaxed ferrite and pearlite while that of the formed component exhibits elongated grains.

***Keywords*—**Laser beam forming, deformation, elongated grains

I. Introduction

LASER Beam Forming (LBF) is a viable process for the shaping of metallic components and a means of rapid prototyping and aligning. LBF is of significant value to industries that previously relied on expensive presses and stamping dies for prototype evaluation. Some of the relevant industry sectors include aerospace, automotive, shipbuilding and microelectronics. In contrast with conventional forming techniques, this method requires no mechanical contact and thus promotes the idea of "Virtual Tooling." It also offers many of the advantages of process flexibility associated with other laser manufacturing techniques, such as laser cutting and marking [1-2]. LBF can produce metallic, predetermined shapes with minimal unwanted distortion. The process has its origin in flame bending for ship construction, with the earliest work on LBF launched in the mid-1980s [3-4]. The LBF Process induces thermal stresses into the workpiece, thereby developing internal stresses. The internal stresses induce plastic strain, bending or shortening the material or result in a local elastic plastic buckling of the workpiece depending on the active mechanism [5]. The LBF process and the parameters are illustrated with Figure 1.

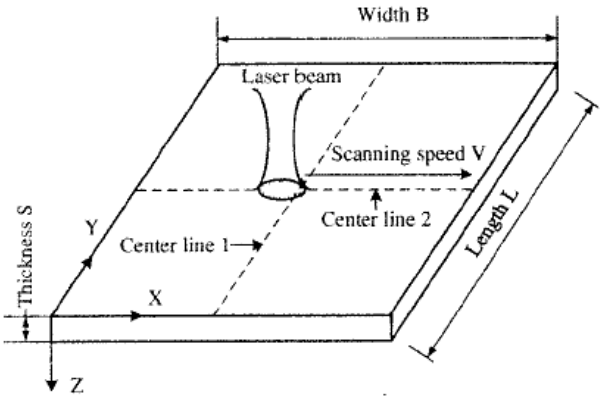

Fig. 1 Schematic diagram of the LBF Process [5]

Since its invention, LBF has been successfully applied to a high variety of sheet metal components from both ferrous and non ferrous metals. Almost 90% of steel manufactured all over the world are carbon steel [6-7]. These materials are widely used in low strength manufacturing, forming and welding applications. Mechanical properties of steels are strongly linked to the microstructure obtained after a heat treatment process [8]. LBF being a form of heat treatment process, effort geared towards characterizing the resulting microstructure and mechanical properties of the formed components is worth it as this will lead to understanding the process-property relationship of the LBF process. The aim of this paper is to successfully use laser beam as a source of heat to form steel plates with a fixed parameter setting, evaluate the microstructure and characterize the mechanical properties of the formed components.

II. Experimental Set-Up

The samples were made from 3 mm low carbon AISI 1008 steel, cut in transverse direction with dimension of 200 x 50 x 3 mm^3. The standard tensile samples were produced from the as received material and tested in accordance with ASTM E-8 standard. A servo-hydraulic Instron 8801 tensile testing machine was used to conduct the test. The composition of the as received material and the formed sample were analyzed by emission spectroscopy using Quantron Advanced Analytical System. The chemical analyses are presented in Table I and II.

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TABLE I
THE CHEMICAL COMPOSITION OF THE AS RECEIVED MATERIAL

Elements	C	Si	Mn	P	S
% by weight	0.025	0.029	0.222	0.0084	0.0082
Elements	Cr	Mo	Ni	Al	Fe
% by weight	0.012	<0.0050	0.0038	0.050	99.59

TABLE II
THE CHEMICAL COMPOSITION OF LBF COMPONENT

Elements	C	Si	Mn	P	S
% by weight	0.138	0.140	0.021	0.050	0.125
Elements	Cr	Mo	Ni	Al	Fe
% by weight	0.049	0.123	0.064	0.125	98.41

The samples were cleaned with acetone to achieve a dirt and oil-free surface before commencing the forming process. An open mould which may be regarded as a fixture in machining operation was designed and employed as the sample holder for support during the process, Figure 2 presents the schematic diagram of the mould with the samples arranged during a forming process. This also enhances full deformation of the samples during the process and allows it to be freely irradiated from either side of the samples.

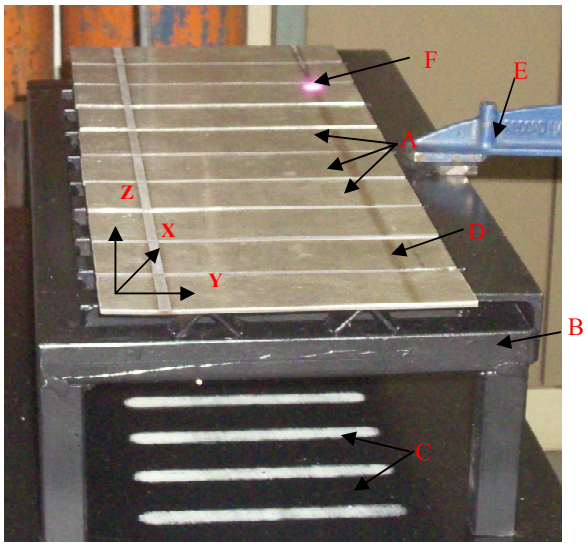


Fig. 2 Schematic set up of the LBF mould and samples

Where,
A= Samples;
B= Mould;
C= Effect of laser heat on the bench
D= Laser irradiation scan;
E= Clamp;
F=Laser beam

A 4.4kW Nd: YAG laser (Rofin DY 044), at the Council for Scientific and Industrial Research, National Laser Centre (CSIR-NLC), Pretoria, South Africa was employed for the forming of all the samples. The samples were successfully formed to about 120 mm curvature at 1.9m/min scan speed, beam diameter of 12 mm, power of 1.7kW, and 25% beam over lap. An argon gas was used to cool the irradiated samples, with the argon nozzle positioned immediately after the laser beam cooling the irradiated surface at a flow rate of 10l/min. The direction of the scanning path is defined as the X- axis, Z-axis as the thickness direction and the y-Axis as the length of the sample. After forming, the samples were sectioned at 100 mm. The sectioned samples of dimension 20 mm x 5 mm were mounted in a polyfast thermoplastic hot mounting resin, grinded and polished to evaluate the resulting microstructure. The microstructure of both the irradiated top surface and the bottom were observed under an optical microscope (Olympus PMG3). The samples were etched in 2% nital by totally submerging the samples for 10 seconds to reveal the grain structure. The grain sizes were measured using the measurement tools on the optical microscope, and the average values of five individual grain sizes were taken. The Vickers microhardness profile was conducted using FM-ARS 9000 automatic indenter according to ASTM 384 standard. The indentations were taken at 0.2 mm below the surface of the irradiated top surface to measure the Vickers microhardness so as to capture the effect of the irradiation, using a load of 300g at a dwell time of 15 seconds. The indentations were taken at 0.3 mm intervals according to the Struers guidelines [9] and all the indentations were manually focused and read to ensure that all measurements were made on the specimen.

III. Results And Discussion

A. Comparative study of the Chemical Composition

The general trend observed in the elemental composition in the chemical composition analysis between the as received material and the formed component was found to increase in the formed component; this can be attributed to the enhancement of the properties of the LBF process whereby improving the elemental composition of the formed component. Presented in Table 3 is the calculated elemental percentage increases as found in the formed components when compared to the as received material.

TABLE III
PERCENTAGE (%) ELEMENTAL INCREASE

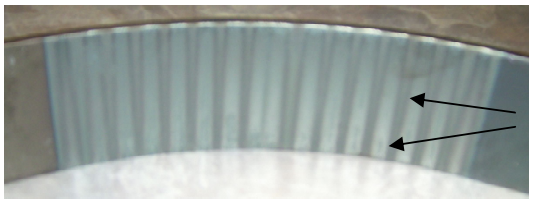
Elements	C	Si	Mn	P	S
% increase	4.52	3.83	-0.91	4.95	14.24
Elements	**Cr**	**Mo**	**Ni**	**Al**	**Fe**
% increase	3.08	23.6	15.84	1.5	-0.01

4.52 % Carbon was the percentage increase by weight of carbon in the formed component. This increase implied that more carbide is likely being formed thereby increasing the steel hardness and strength. The increase in some of the other elements such as Silicon, Chromium, Molybdenum, and Nickel further confirmed that the strength and hardenability of the formed component was not destroyed during the process, rather it was improved based on the measured percentage increases. On the other hand, no elemental increase was observed in Manganese but the presence of Molybdenum and

Chromium was significant which effectively compensated for absence of Manganese. The presence of the three elements was meant to improve the strength and hardenability at high temperatures.

B. Top and Bottom surface appearance of the formed components

The formed sample shown in Figure 3 (a) and (b) is the top surface appearance of the irradiated surface and the bottom surface respectively.



(a)

(b)

Fig. 3 (a) Top and (b) bottom surface appearances of formed component

The top surface shows the irradiated scans clearly because the surface was directly irradiated with the laser beam while the faint scan tracks observed at the bottom was a reflection of the heat absorbed from the top surface. The isotherms are also indication of absorption of heat across the material thickness. This is a strong indication that the irradiated top surface captured sufficient heat across the material thickness without melting.

C. Microstructural Evaluation

The evaluation of the microstructures of the as received material was conducted before the commencement of the LBF process as a baseline to monitor the structural changes as a result of the LBF process and for comparison purposes, to determine the effect of the process on the structure of the materials. It was observed that the microstructure of the as received steel plates was ferritic and characterized with equiaxed grains evenly distributed; this is shown in Figure 4.

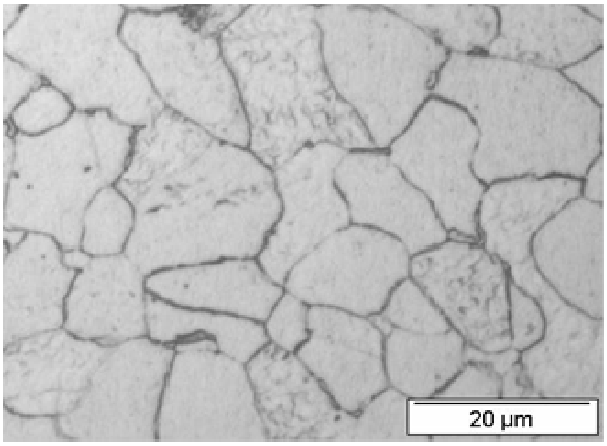


Fig. 4 Microstructure of the as received material showing equiaxed ferrite grains and pearlite

The microstructure of the top and bottom of the formed sample shown in Figure 5 (a) and (b) is a representative sample from the top irradiated surface and bottom.

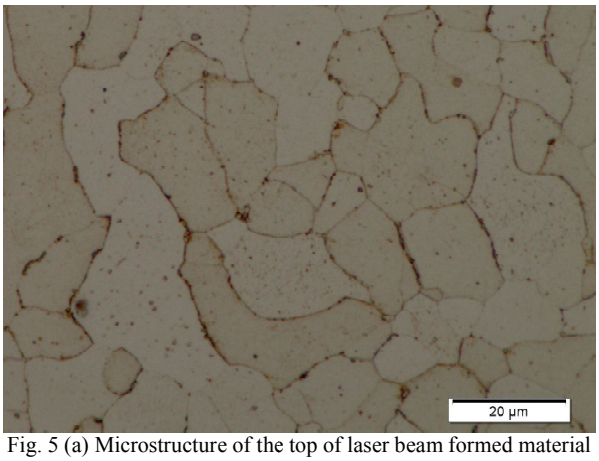


Fig. 5 (a) Microstructure of the top of laser beam formed material showing elongated ferrite and pearlite grains

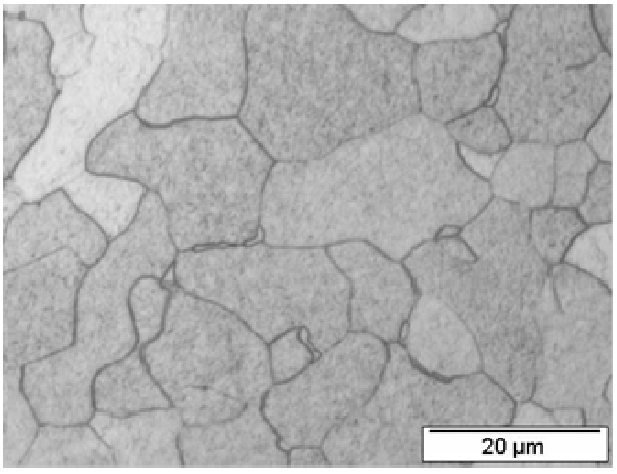


Fig. 5 (b) Microstructure of the bottom of laser beam formed material showing elongated ferrite and pearlite grains

It is evident from the observation of the elongated grains in the microstructures of the top irradiated surface and bottom laser formed samples that the sample has gone through a significant structural change when compared with the microstructure of the as received material. This microstructural changes may be explained by the process of heating the material above its upper transformation temperature whereby the ferrite grain re-crystallizes; as such the microstructure was transformed from the equiaxed ferrite matrix as established in the as received material to an elongated grain structure shown in Fig 5 (a) and (b). The development of this elongated grain structure can be regarded as grain growth. Similarly, the grain sizes measured on the irradiated surface were found to increase from 25.61 µm (as received material) to an average grain size of 32.32 µm (formed component). Following the observation of the microstructure of both the top and bottom surface of the formed component under the optical microscope, no significant change was observed in the microstructures because both experienced grain elongation. There were also no significant changes in the grain sizes of the irradiated surface and the bottom following the measured grain sizes.

D.Mechanical Properties

Tensile testing is widely used to provide key information on the strength of materials. The results from the test are commonly used to select a material for an application, for quality control, and to predict how a material will react under other types of forces. The tensile samples were produced from the as received material and tested. The stress-strain graph of the three samples of the as received material is shown in Fig 6 from which the Ultimate Tensile Strength (UTS), Yield Strength (YS) and strain were determined.

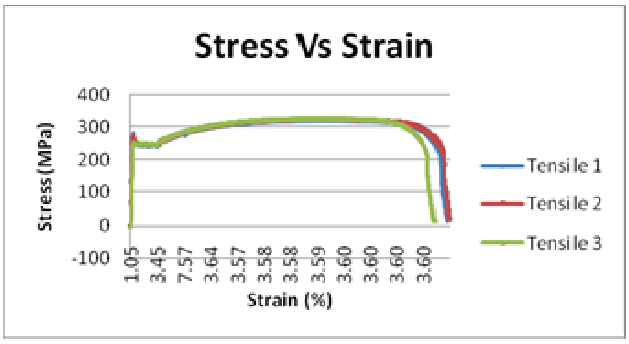


Fig 6 Tensile behavior of the 3 mm as received material

The mean UTS, yield strength and percentage elongation of the three tensile samples are presented in Table IV. T_1, T_2, and T_3 represent the three samples tested.

TABLE IV
TENSILE RESULTS FOR THE AS RECEIVED MATERIAL

	T1	T2	T3	Mean
UTS (Mpa)	320.96	324.38	326.90	324.08
YS (Mpa)	282.15	269.47	252.91	267.91
% Elongation	46.92	46.04	45.30	46.09

All the specimens were tested to failure. The mean percentage elongation of the as received material was found to be 46.09% which is a measure of the ductility of the material.

The UTS for the formed component was estimated from the relationship between Vickers microhardness and UTS which was developed by Knupfer and Moore [10], the relationship is expressed by equation 1.

$$UTS = 9.81\left[\frac{H}{2.9}\right]\left[\frac{n}{0.217}\right]^{n} \quad (1)$$

Where,
H = Vickers microhardness
n = Strain hardening index which is 0.21for low carbon steel (annealed).

Presented in Table V are the calculated and experimental values of the Ultimate Tensile Strength and microhardness of the as received and laser beam formed component.

TABLE V
SUMMARY OF CALCULATED AND EXPERIMENTAL VALUES

Average Values			
	As received	LBF	% Increase
Microhardness	94	134	42
Experimental UTS	324.08	-	-
Calculated UTS	317.6	431.79	36
% error for AR	2	-	

The calculated UTS value (317MPa) for the as received material was within acceptable error value of less than 2% of the experimental value (324MPa). The tensile test for the LBF components is ongoing; we are currently designing the fixture for the formed component on the tensile machine. As such the calculated UTS values was employed to establish the relationship between UTS and Vickers microhardness. An increase in the calculated UTS was observed in the as received material (317MPa) compared to the formed component (431MPa). This increase can be correlated to the increased Vickers microhardness which can be due to the enhancement characteristic of the LBF process. This claim can be further supported by the observed elemental increase in Carbon after the LBF process. The increase in the hardness values is due to the continued carbon dissolution from the pearlite and formation of bainite. Consequently, the results of the microhardness measurements and tensile tests reveal that the magnitude of hardness and Ultimate Tensile Strength is dependent on the mutually interactive influences of the resistance offered to the motion of dislocations, and the plastic deformation capability of the metal matrix. The Vickers microhardness profiles were measured. The microhardness profile for both the as received material and the Laser formed component are shown in Figure 7.

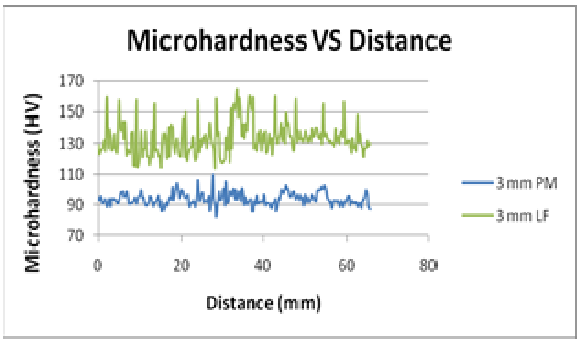


Fig 7 Microhardness profiles of the cross sections of the as received material and the Laser formed component

The profiles show that the Vickers microhardness values ranges between 82 HV and 109 HV for the as received material and between 114 HV and 164 HV for the formed component. This can be attributed to the effect of the LBF process on the material during which the heating and cooling alters and affect the Vickers microhardness of the material. The profile also shows an average value of 94 HV for the as received material and an average of 134 HV for the Laser formed component. This significant increase in the microhardness value can be attributed to plastic deformation and mechanical working during the forming process.

IV. Conclusion

Laser beam forming when considered as a form of heat treatment process it is used to obtain desired properties of steels such as improving the toughness, ductility or improving the residual stresses. The effect of the process resulted to microstructural changes from equiaxed to elongated grain structures, also exhibit a significant change in the microhardness with 42% increase from the as received material compared to the formed component. The Ultimate Tensile Strength of the material was improved by 36% due to the carbon dissolution from the pearlite. Further studies to establish the phase transformation during the LBF process and SEM analysis are currently underway.

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