Material Characterization Studies on the Laser Beam Formed AISI 1008 Mild Steel

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***Abstract*— Laser Beam Forming is a new non-contact method without the use of a die, to achieve deformation in metals, which traditionally involved the application of mechanical forces to change the shape and form of the material permanently. Laser forming causes deformation by introducing thermal stresses from an external heat source as opposed to the simple application of forces in mechanical forming. In this study, samples were formed mechanically by using a dynamic press brake machine, whereby, a punch and die apply the force. A 4.4 kW Nd:YAG laser system was used to form a second set of samples made from cold rolled AISI 1008 mild steel using laser forming. In this collaborative work involving researchers from the USA, South Africa and India, the mechanical and metallurgical properties of the unformed, mechanically formed and laser formed samples were experimentally investigated. The objective is to compare these properties amongst the different samples in order to analyze the impact of the varying methodologies especially the laser energy effects on the samples. The conclusions from these tests have provided valuable information on the applicability of laser forming to attain the appropriate surface modifications yielding the desired mechanical and metallurgical properties of the metal.**

***Keywords*— AISI 1008 Mild Steel, Laser Beam Forming, Mechanical Forming.**

I. INTRODUCTION

AISI 1008 rolled mild steel is used for many applications, and heavily in automotive and industrial applications because of its ability to be formed [1]. Consequently, the ability to easily and cheaply form steel with precision is extremely valuable. Forming is a process that introduces external forces to a material which results in a desired plastic deformation. Mechanical forming (MF) and laser beam forming or laser forming (LF) are two types of forming processes, with MF being the most common and widely used [2]. MF is a process that is conducted at room temperature to form the desired material by applying external contact forces to form it to the shape of a die. Mechanical forming allows parts to be easily produced en masse with consistent properties and surface finish throughout the metal with no shrinking or creeping. But limitations of mechanical forming is that contact is required with the part as well as a die is required to be made before a part can be formed. It is limited to the shapes that can be formed with each punch, and there is often repositioning of the part required to achieve the desired bending. The mechanically formed samples studied were formed using a dynamic press brake machine with a 20 ton capacity. The eccentric mechanical press used to form the samples is located at the Nelson Mandela Metropolitan University, Port Elizabeth, South Africa.

Laser forming is a relatively new forming process, which deforms material by introducing thermal stresses to selected regions causing bending towards the laser source [3, 4]. When the laser contacts the surface of the metal, it is heated initially causing some counter bending away from the laser source. After the laser passes, the metal rapidly cools and the positive bending towards the laser source results. The advantages of laser forming is that it is a non-contact forming process requiring no die and allowing for accuracy in a large variety of shapes form just one scan without repositioning of the part. The laser may also be used to strengthen weak areas of a part while forming it. There has been very minimal research into the properties of laser formed materials, so the applications and advantages of laser forming are not yet fully discovered [5]. The laser formed samples acquired and studied were formed at the CSIR-NLC in Pretoria, South Africa using a Rofin DY 044, 4.4 kW neodymium-doped yttrium aluminium garnet laser system [6].

Conducting a material characterization study of the laser beam forming on AISI 1008 mild steel will allow the laser forming processed steel to be compared to the mechanically formed processed steel. Taking a surface measurement will give a quantitative value to the texture on the surface of a material, giving data about the profile of the surface [7].

The microstructure of a material is a qualitative testing method which shows the structure of the grains in the metal through either optical or electron microscopes. The metal's grain size and shape have a great impact on many properties of that metal including the strength, hardness, toughness and other properties. Generally, when the grain size decreases, the strength, hardness and also brittleness of that metal is consequently increased. In many situations, it is beneficial for a metal to have a surface that has high hardness and toughness to protect against wear, and for its middle portion to maintain the original properties of ductility and higher yield strength. Hardness measures the resistance that a material has to indentation from a specifically shaped indenter. A metal that has a higher hardness has a higher toughness and resistance to wear, scratches, and denting. The hardness measurement is an easy measurement to take that gives insight into the strength, ductility, and toughness of the tested material [8]. These mechanical and metallurgical properties constituted the material characterization studies on the AISI 1008 mild steel reported in this paper.

II. Samples and Testing Methods

A parent material sample, mechanically formed sample and three laser formed samples originally 200 x 50 x 4 mm^3 were bent under three separate laser conditions were analyzed in this research. The samples and the known data for each are shown in Table I, as well as the energy densities [9] for each laser formed sample in Table II. It can be readily seen that two of the laser formed samples labelled P4 and P16 were under similar energy density while P20 was formed at approximately 50% higher energy density.

TABLE I:
SAMPLE INVENTORY AND DESCRIPTION

Samples →	Parent	MF	LF P4	LF P16	LF P20
Number	4	2	3	2	2
Laser Power, W	-	-	1800	2400	3000
Beam Dia, mm	-	-	15	15	12
Scan Speed, (m/min)	-	-	0.08	0.11	0.11
# scan irradiation	-	-	3	1	3
Argon cooling rate, L/min	-	-	5	15	10
Curvature Dia, mm	-	240	1993.5	1219.9	1280.7

TABLE II:
ENERGY DENSITY CALCULATION

Sample	Laser Energy Density (J/mm^2)
(LF) P4	114.59
(LF) P16	111.12
(LF) P20	173.62

In each test that was conducted on the laser formed samples, data was taken for both the laser contacted regions and the non-laser contacted regions. The different regions observed on the laser formed samples are as indicated in Figure 1. This would allow not only the difference in laser formed metal to be seen compared to mechanically formed, but also variations within one laser formed part to be seen.

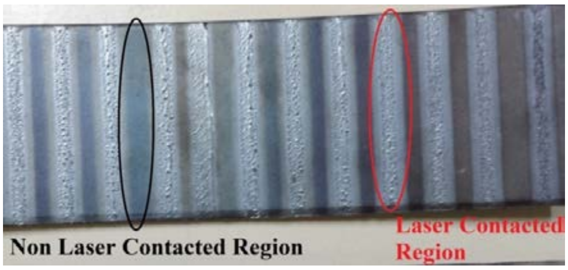

Fig. 1. Identification of Laser and Non-laser contacted regions

A. Surface Roughness Testing

Surface roughness measurements were taken on a Taylor Hobson Precision Form Talysurf 50 Profilometer [10]. This machine uses a diamond stylus that moves along a vertical surface for a determined distance reading the vertical displacement of the stylus caused by the surface's profile. The produced value from this test that was used was the average roughness, R_a value. Tests were conducted on both the laser contacted regions as well as the non-laser contacted regions of the laser formed samples, to allow for comparison of the two regions within each sample. The non-laser contacted regions were expected to have a much lower roughness than the laser contacted regions of the laser formed samples. The P4 and P16 samples were expected to have similar R_a values as the mechanically formed. The P20 sample appeared to have had melting and bubbling of the metal's surface occurs resulting in a very rough surface.

B. Metallurgical Testing

In preparation for investigating the microstructure of the samples, 10 mm x 5 mm pieces were cut from each sample in laser and non-laser regions to inspect the surface of the metal. Also, a 5 mm x 5 mm piece of laser contacted region from each sample was cut to inspect the cross-section of the laser contacted portion of the steel. The cut samples were then mounted in a polyfast to allow easier polishing of the samples for etching and hardness testing. After the samples were polished, they were etched in a solution comprised of 2.5 ml of nitric acid and 50 ml of ethanol for 15 to 20 seconds to allow the grain boundaries to be seen under the optical microscope. The samples then were all viewed under the optical microscope at a power of 200x magnification. The laser contacted regions were expected to show smaller grain size than in the non-laser regions and mechanically formed samples. And the higher laser powers to also have smaller grain size that lower powers. The laser formed samples were expected to have very similar grain size to the mechanically formed sample, and much smaller grain size than the parent material.

C. Hardness Testing

The method used for testing the hardness of the steel samples was the Vickers hardness test. Vickers hardness test is an easy test to run since it is independent of the size of the indenter and can be used on any metal. Vickers is a micro indentation test which uses a pyramid shaped diamond indenter which has a 22º angle on the horizontal plane. The Vickers Pyramid Number (HV) is the resulting hardness value from the test. The HV value found by a ratio of the force applied by the diamond indenter over the area of indentation left behind [8]. For the tests ran on these steel samples, a force of 5 kgf was applied for 10 seconds, then the horizontal and vertical diameters of the indentation left were measured under the microscope allowing the HV value to be calculated.

III. Results and Discussion

A. Surface Roughness Evaluation

The results of the surface roughness tests presented in Table III did show that the non-laser regions had significantly lower R_a values than the mechanically formed samples.

TABLE III:
SURFACE ROUGHNESS VALUES FOR ALL SAMPLES

Surface Roughness	
Laser contacted ID	
	Ra (µm)
P4	0.767
P16	0.544
P20	1.586
Non Laser Contacted ID	
	Ra (µm)
P4	0.628
P16	0.519
P20	0.502
	Ra (µm)
PM	0.501
MF	0.983

In the laser contacted regions, the surface roughness was much lower for the two lower powered samples. But the high laser powered samples had extremely high roughness in the laser contacted regions. The two lower power lasers had low R_a values because when a metal is heated and rapidly cooled it will result in a smoother surface, but in the case of the high laser powered sample the temperature reached high enough on the surface of the metal to cause it to start to melt and bubble, resulting in a very rough surface of 1.586 µm. So when the laser is used at the correct power it will create smoother surface on the part that is created in the traditional mechanically formed part. From this data, the P16 sample appears to be the optimum laser power to achieve a surface finish closest to that of the parent material.

B. Microstructural Characterization

The results of the microstructure analysis under the optical microscope showed grain structure very similar to what was expected. The images can be seen in Figure 4.

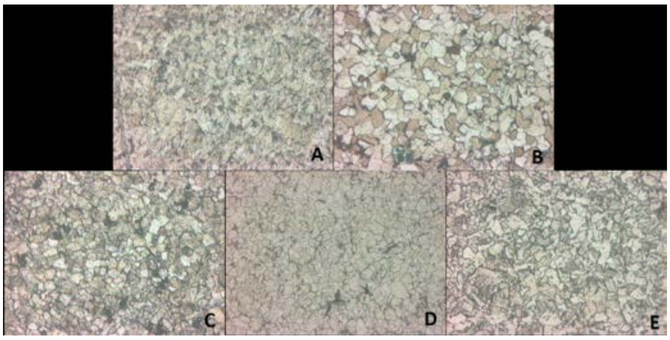

Fig. 2. Microstructure visible through the optical microscope at 200x magnification: A) Mechanically Formed B) Parent Material C) P4 laser contacted region D) P16 laser contacted region E) P20 laser contracted region

The grain size in the laser formed samples show that the grain size is virtually the same as mechanically formed sample. But because of the rapid cooling after laser contact, martensite is present [11] which should give the metal more strength and hardness as seen in the hardness results to come. Although, in (E) the grain has become slightly larger and elongated, this is the highest laser power which had some melting that occurred on the top layer of metal. Because of this melting and rapid cooling at the top surface, there is more martensite present, so this sample should have the highest strength and hardness, which is seen in the hardness tests later. In Figure 3 the top, middle and bottom microstructures of the cross-section of sample P20 are shown.

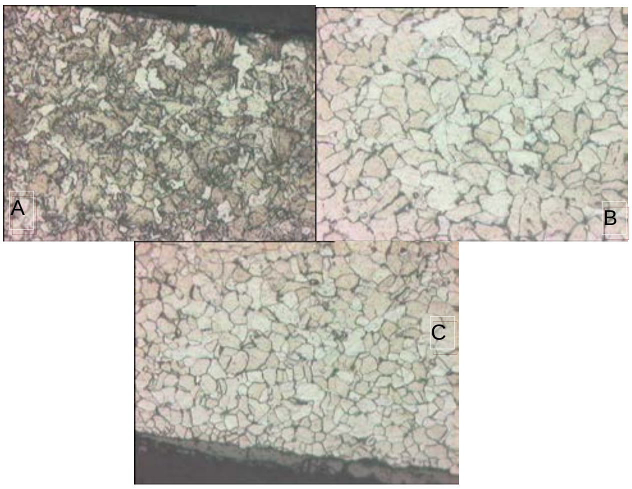

Fig. 3. P20 cross-section A) top B) middle C) bottom

It can be seen in Figure 3A that the top layer has smaller grain size and what appears to be martensite that has formed, but then in Figure 3B at the middle of the cross section, the grain appears to be larger and more similar to that of the parent material. Finally in Figure 3C at the bottom of the cross-section which is the side of the sample opposite where the laser contacted, the grain size is smaller, but lacking the martensite that was at the surface. This suggests that the strength and hardness of the metal at the top and bottom will be higher than at the middle, similar to that of a surface hardened metal. The reason for this is that when the cross-section is headed from the laser and the laser is removed, the top and bottom are rapidly cooled by the air resulting in finer grains, and the middle is cooled slower allowing for some grain growth.

C. Vickers Hardness Profiles

The final results are the hardness results seen in Tables IV and V. These results came out just as anticipated. The laser contacted regions were expected to have the highest hardness values in all the samples and to show higher hardness than the mechanically formed. This should be due to the heating and rapid cooling of the laser regions. The hardness values of the cross-section should decrease as it gets farther from the laser contacted surface because farther from that surface will have reached lower temperatures, and also will have cooled slower than at the surface. As the laser power was increased the hardness increased also which is congruent with the microstructure results.

TABLE IV:
HARDNESS VALUES

Sample	Hardness (HV)
PM	138.0
MF	125.5
P4	132.5
P16	136.5
P20	152.3

TABLE V:
HARDNESS VALUES THROUGH THE CROSS-SECTION (CS)

Sample	Hardness avg. (HV)			
	Surface	Laser CS	Middle CS	Opposing CS
P4	139.9	137.0	129.9	130.4
P16	137.3	129.7	124.9	127.3
P20	164.2	135.3	126.9	129.1

Table 5 shows that the hardness results are congruent with the microstructure results for the cross-section. The surface provided the highest hardness which decreased at the middle, and then increased hardness is seen at the opposing side again.

D. Observation of the Formed Samples

The laser contacted regions were also more resistant to rust than the mechanically formed metal. This is because of the rapid cooling of the metal, similar to a quenched metal which is more resistant to rust. The down side is that the non-laser contacted regions are then prone to rust more quickly than both the laser regions and the mechanically formed samples. This phenomenon can be observed in Figure 4.

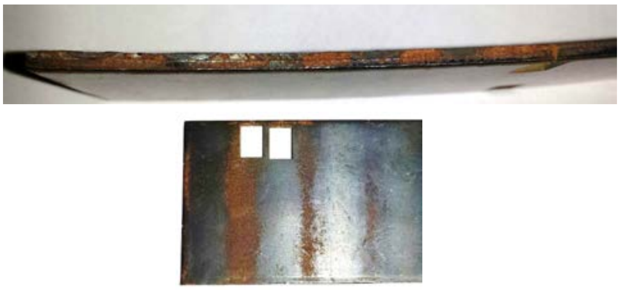

Fig 4. Rusted non-laser contacted regions

The rust observed in the non-laser contacted regions in this case is attributed to the fact that the laser scanning was conducted with zero percent overlap, more studies are required to conduct laser forming with certain percentage of overlap in order to fully eliminate non-laser contact regions in the formed samples thereby reducing the degree of rust.

IV. CONCLUSION AND RECOMMENDATIONS

Laser forming when used at the optimum laser power and located correctly can be a very beneficial process with properties similar to and exceeding those of the traditional mechanical forming process. It can be used not only for bending, but also for hardening, and strengthening of specific regions of parts [12,13]. This could be a very beneficial technology in the automotive industry for door panels, hoods and other panels. The lasers can be used to treat the surface of the door to create a harder surface that is more resistant to scratching and denting.

In this research, the three laser formed parts that were studied have many variables among the three samples with the laser power, beam diameter, scan speed, number of scan irradiations and cooling rate all varying for every sample. If all variable were held constant except one, then it would be possible to investigate how each variable has an effect on the properties of the metal, allowing an optimal set of parameters to be used in the forming of AISI 1008 steel.

In future research, it would be beneficial to look at the macro view of the laser formed metal. While the micro view of the laser formed steel was comparable to the mechanically formed, this may not be the case once the parts are put into an applied or actual situation. So in the future laser formed parts need to be tested in real situations under actual loads to investigate how they will withstand applied situations.

ACKNOWLEDGMENT

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