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# Metallographic Analysis of Laser and Mechanically Formed HSLA Steel

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***Abstract*—**This research was conducted to develop a correlation between microstructure of HSLA steel and the mechanical properties that occur as a result of both laser and mechanical forming processes of the metal. The technique of forming flat metals by applying laser beams is a relatively new concept in the manufacturing industry. However, the effects of laser energy on the stability of metal alloy phases have not yet been elucidated in terms of phase transformations and microhardness. In this work, $CO_2$ laser source was used to irradiate the surface of a flat metal then the microstructure and microhardness of the metal were studied on the formed specimen. The extent to which the microstructure changed depended on the heat inputs of up to 1000 J/cm$^2$ with cooling rates of about 4.8E+02 K/s. Experimental results revealed that the irradiated surface of a HSLA steel had transformed to austenitic structure during the heating process.

***Keywords*—**Laser, Forming, Microstructure

## I. Introduction

THE technique of bending or forming the flat metal sheet by applying a laser beam is a new concept in the manufacturing industry. Traditionally, manufacturing industries apply mechanical methods to cold work or hot work metals into specific shapes. It is well known that the process of bending flat metal sheets induces phase transformations that affect material properties. The changes in grain structure and size at the angle of bend invariably alter the strength of steel. At the bending point, the microstructural features on the outer surface get elongated; those at the centre remain the same while the inner surface microstructural features get compressed. In order to reduce the unintended effects of these stresses during forming, the steel may be heated prior to forming and kept at a substantially high temperature so as to minimize the development of internal stresses during bending.

Several authors have shown that the application of lasers in metal forming processes leads to high productivity because the number of stages in the manufacturing processes are reduced [1-2]. Laser forming constitutes a process of forming metal shapes without mechanical contact by using the laser beams. This implies that the target metal plate is irradiated with a laser beam directed to the metal surface at a specific beam velocity along a path known as the bending edge. Although laser forming is known to yield better quality products in comparison to mechanical forming methods, researchers have reported that during laser forming localised internal temperature gradients are generated across the thickness of the metal at the bending angle [2]. Therefore, laser application must be optimised to ensure a uniform distribution of energy across the target metal. Correct temperature distribution can be achieved by optimal combination of laser intensity, velocity, and beam diameter for a specific metal thickness [5]-[6]. Magee et al. [3] has conducted research to improve the dimensional accuracy of parts produced using laser forming. Li and Yao [4] studied the quality of laser induced bends of tubes and found that the bending radius was governed by the laser beam diameter. Chan et al. [2] studied the effects microstructure of hardened high carbon steel during laser forming, they came out with conclusion that the microstructure and the microhardness profile of the sheets deformed at both low- and high-energy inputs. The effect of laser application on the microstructure and properties of a target material has been reported for mild steel as well [7].

In this study, we attempted to compare the microstructure and microhardness profiles of mechanically formed and laser formed HSLA steel. In this regard, a 5kW $CO_2$ laser was used to bend a 3.5mm thick sheet sample to a 120mm curvature. The phase transformation was studied in the target materials and made a correlation between the phase changes and resultant microhardness. The target material was a High Strength Low Alloy (HSLA) metal sheet which was used to make wheel parts in the automotive industry.

## II. Procedure

### A. Material

The starting material used in laser forming was a 3.5mm thick HSLA steel sheet with the standard chemical compositions as shown in Table I. This material is known as niobium micro alloyed steel used in the automotive industry for the manufacture of wheel parts.

TABLE I Chemical composition in wt. % of the standard HSLA steel used in the wheel manufacturing [8]

| | C | Mn | Si | P | S | Nb |
|---|---|---|---|---|---|---|
| **A715** | 0.150 | 1.650 | 0.010- | 0.025 | 0.035 | 0.005- |

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*B. Experimental*

A verification of the chemical elements was made by analyzing the sample composition using Sparck Analyser machine. The elemental compositions of original laser-treated steel and mechanically worked steel are documented as shown in Table II.

TABLE I THE MATERIAL USED AND THEIR CHEMICAL COMPOSITION IN WT%

| Material | C | Mn | Si | P | S | Nb |
|---|---|---|---|---|---|---|
| Laser Formed | 0.090 | 0.836 | 0.096 | 0.036 | 0.011 | 0.031 |
| Mechanically formed | 0.088 | 0.809 | 0.016 | 0.011 | 0.004 | 0.028 |

Laser forming was carried out using a 5kW $CO_2$ laser and the scanning parameters were as follows: power (1kW), velocity (0.475 m/min), beam diameter (8 mm), interval spacing (8 mm) and 0% overlap between scans. Laser formed specimens were de-scaled by pickling in 10% HCl at a temperature of 75°C prior to standard metallographic sample preparations.

The specimen as shown in Fig. 1 was sectioned along the bending curvature to obtain samples for metallographic analyses. All the samples were prepared using standard metallographic methods and etched in 2% nital. Metallographic analyses were carried out using an optical microscope and the grain sizes were measured using the plenimatric method. Finally, microhardness measurements were carried out on the metallographic samples.

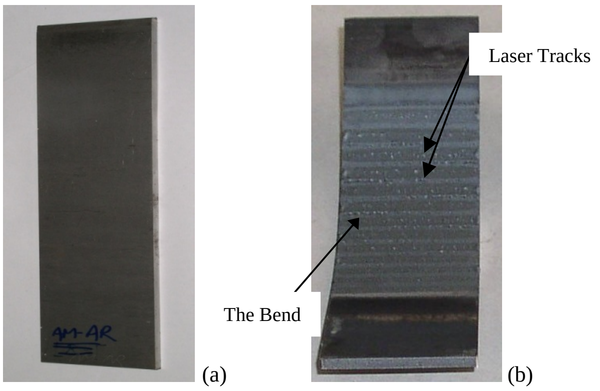


Fig. 1 The flat untreated sheet (a) and the laser formed sample (b)

## III. RESULTS AND DISCUSSIONS

*A. Chemical Composition*

In order to establish the original composition of the starting material, the elemental analysis of metal samples was determined prior to laser application. The results in Table II provide sufficient evidence that this steel is a Niobium HSLA steel since only niobium was detected as the micro alloying element. A significant difference from the determined values was on the basis of silicon composition. It is well known that excess silicon in the commercial steels forms non metallic inclusions ($SiO_2$) as it combines with the oxygen. However silicon tends to dissolve in the ferrite, increasing the strength of the steel.

*B. Microstructural Characterization*

The morphology of the specimen that was laser formed obtained from a stereo microscope shown in Fig 2, indicates the heat effect after irradiation. The surface appearance of the metal at the point of irradiation at the top surface was different from the area towards the bottom surface. The degree in structural differences of the general structure highlights the heat effects across the thickness of the steel.

When considering the microstructures of the laser formed samples as illustrated in Fig. 2 (a, b, and c), it is evident that the specimen revealed a significant degree of change in microstructure from the irradiated top surface and towards the bottom surface. The maximum temperature during laser forming was about 1377.7$^o$C when irradiating the steel with the laser beam [**[9]**]. At this temperature, the HSLA steel gets transformed to austenitic phase and on cooling the austenite transforms to ferrite depending on the rate of cooling. The extent to which the microstructure changed depended on the heat inputs of up to 1000 J/cm$^2$ with cooling rates of about 4.8E+02 K/s. When the beam was removed, there was cooling on the irradiated surface but some of the heat started to temper the steel just below the top surface, creating the isotherms.

The top surface from the inner part of the curvature shows that the specimen captured most of the heat supplied by the laser beam. In this specific region, a significant grain growth or coarsening and phase change was observed as shown in Fig. 2 (a) of the laser treated specimen as compared to the original flat steel specimen. The grain size analysis indicated that the grain size was increased to ASTM Number 10 with an average grain diameter of 9.57µm at the top surface. The microstructure was transformed from an equiaxed ferrite matrix to a Widmanstatten structure. The steel was therefore heated above its upper transformation limit as the ferrite grains have re-crystallized.

In the centre of the sample Fig. 2 (b), the structure of the laser treated specimen had coarsened with small grain size changes compared to the original flat steel sheet. The grain size within the centre part increased to ASTM Number 11 with an average grain diameter of 8.07µm when compared to that of the flat specimen with an average grain diameter of 4.30 µm. The phase change was not evident as an equiaxed ferrite matrix with fine pearlite at the grain boundaries was observed.

There was also an insignificant phase change in the structure of the laser treated specimen at the outer part of the curvature (bottom surface) as shown by Fig. 2 (c). However, an increase in grain size was also note as the specimen has an average grain diameter of 7.39 µm with ASTM Number 11. These structural changes are induced by factors including the applied heat, metal cooling rates and plastic strain.

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Fig. 3 shows the photomicrograph of the original flat steel metal. On the basis of the visual appearance, the microstructure of this specimen is a fine grained ferrite (white phase) and pearlite (darker regions mainly along the grain boundaries), uniformly distributed through the thickness of the steel. The average grain size of the material was therefore ASTM number 13 with a calculated value of the average grain diameter of 4.30 µm. These results formed the bases for the comparison after the heat treatment during laser forming. The fine grain size has direct impact on the high strengthening properties of the material. This is due to dispersion strengthening by the fine niobium carbides.

The microstructure in Fig. 4 of the mechanically formed piece of a HSLA specimen also showed the fine grained ferrite (white phase) and pearlite (darker regions along the grain boundaries). The phases were homogeneously distributed through the thickness of the steel. The ferrite grains dominated the matrix with finer grains of pearlite on the grain boundaries. The results summarized in Table III indicate that average grain size was therefore ASTM Grain Size Number 13 with a calculated value of the average grain diameter of 4.50 µm, which also justifies the argument that the material was fine grained.

The optical metallographic analyses across the thickness of the steel parts also confirmed the existence of different morphologies that extent across the thickness of the steel, from the point of irradiation (at the top surface) towards the interior of the specimen due to heat effects. When comparing the laser formed parts to the mechanically formed parts, mechanically formed samples have a homogeneous surface structure i.e. the grain size and phases across the thickness remained the same.

### *C. Microhardness Tests*

The specimens were tested with Vickers microhardness tester; the indentations were obtained and measured to represent position through the thickness of the specimen as obtained in the microstructural analysis. The microhardness values through the thickness of the flat sheet steel mechanically formed and laser formed specimen yielded results shown in Table III. The results show reduced hardness values on the irradiated surface of laser treated specimen. This is due to the heat affect on grain growth of the steel and thus brought about softening. The hardness decreased significantly by 10% as compared to the flat sheet steel. However, there was no significant phase change in mechanically worked steels and the increase in hardness averaged 6% as compared to the hardness of the flat sheet.

In the work by Hulka [4], the microstructure of the Niobium HSLA steel has been characterized by reviewing cooling rates on the time-temperature-transformation (TTT) diagram in Fig. 5. The diagram provides information on the different phases that may be obtained when varying the heating temperature and cooling rate. The ferritic and bainitic microstructures are readily obtained on when cooling the metal between $10^2$ and $10^4$ seconds. This confirms the relationship between structural phase and hardness values obtained from the investigations carried out in this study.

On comparing laser formed specimen to the mechanically formed specimen, it is evident from the microhardness values that mechanically formed specimen have uniform structural properties. The microhardness values above 200HV range provides good mechanical properties. However, after laser forming, the structural changes due to heat treatment have decreased the mechanical properties of the steel as summarized in the Table III.

The local yield strength was calculated from the hardness values obtained using an empirical equation derived on the basis of the Ludwik-equation [11]. The results showed the calculated yield strength in different specimen from the hardness measurements. The decrease in hardness and yield strength after laser forming indicates a high dislocation density due to work hardening. This can be controlled by evaluating the cooling methods to control the cooling rate to form bainitic structures.

## IV. Conclusion

By comparison, the laser treated steel and mechanically formed steels yielded different microstructural phases and thus exhibited significant differences in microhardness values. The phase change in laser steels varied from a fine-grained ferrite to predominantly coarse-grained ferrite at the irradiated surface and therefore, the hardness decreased significantly. It is evident that after irradiating the metal, the heat penetrates the sample and the sample is self cooled allowing slow cooling of the metal forming larger grains. In this study an 8mm beam diameter with 0% overlap between scans was used and further studies have being carried out varying laser forming parameters in order to enhance the mechanical properties of the laser formed HSLA steel sheets.

## Acknowledgment

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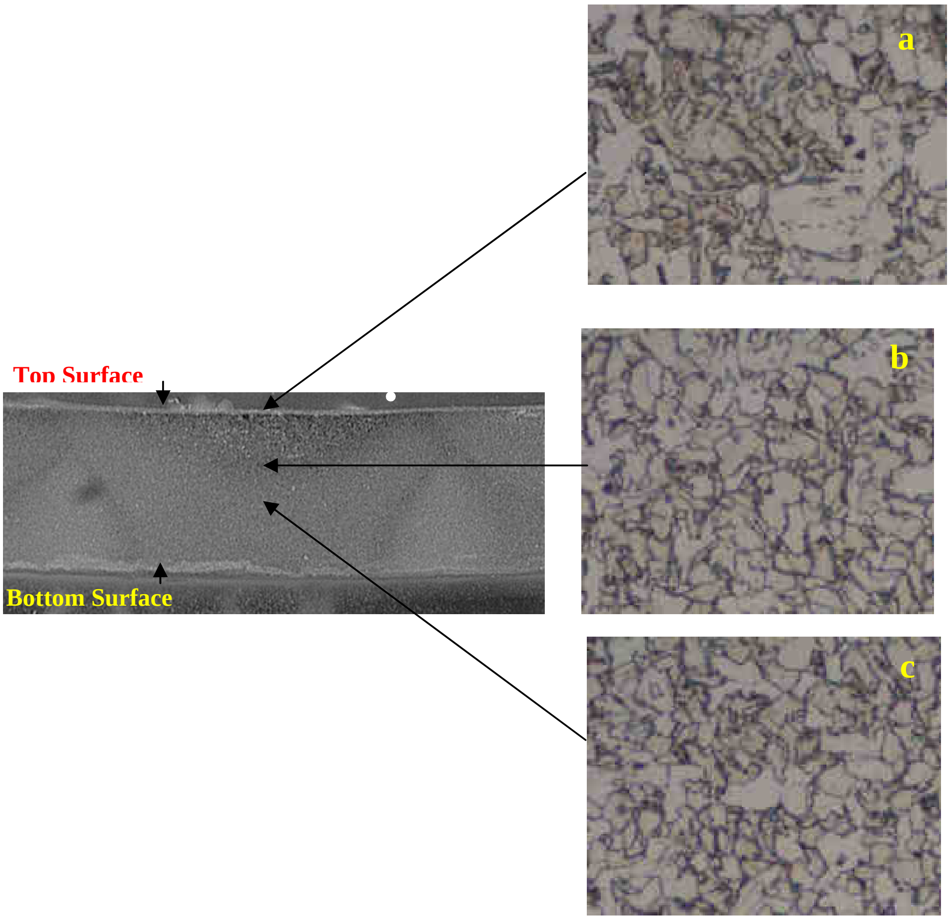



Fig. 2 An image from an optical stereo microscope of the laser formed specimen with poor fatigue performance LF-8mm, with micrographs at 200x from the top surface a) first isotherm b) second isotherm and c) the third of the isotherm.

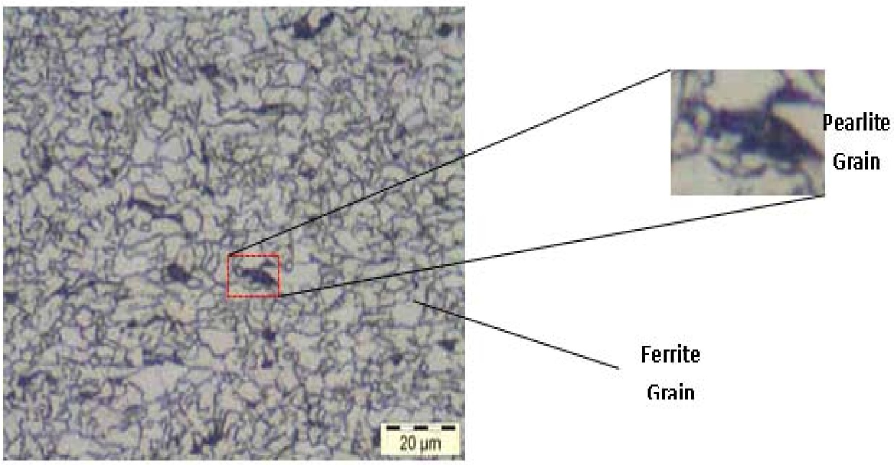
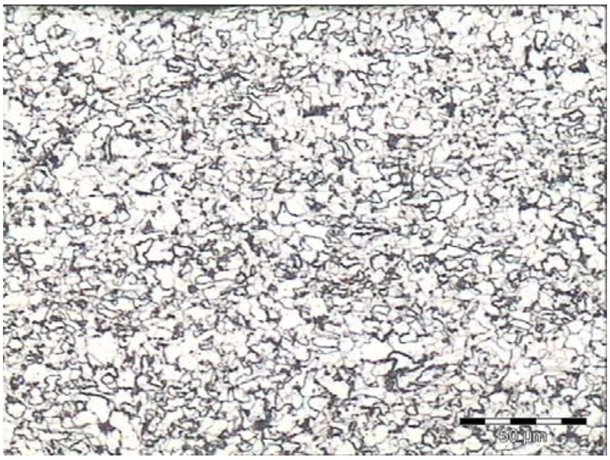
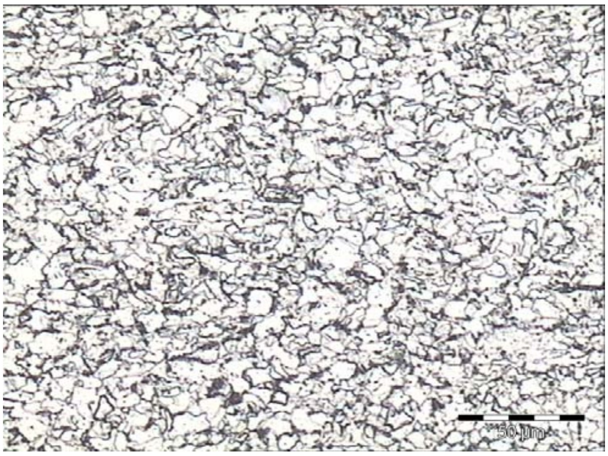


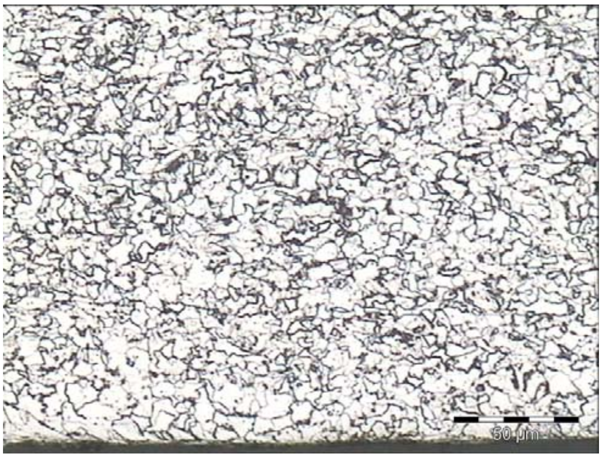

Fig. 3 An image from optical microscope of the flat untreated specimen, with micrographs at 500x



**(a)**



**(b)**



**(c)**

Fig. 4 Microstructures for mechanically formed specimen across the thickness of the sample, at 200x

TABLE II SUMMARY OF THE MICROSTRUCTURAL AND STRENGTH PROPERTIES ANALYZED

| **Specimen** | **Phases Present** | **ASTM No.** | **Ave. Grain Diameter** (μm) | **Hardness (HV:0.1)** | **Yield Strength (Mpa)** |
|---|---|---|---|---|---|
| Flat Sheet | Equiaxed Ferritic matrix – Fine Pearlitic | 13 | 4.30 | 185 | 466.60 |
| Mechanically Formed | Ferritic - Pearlitic | 13 | 4.50 | 214 | 564.04 |
| Laser Formed | Top: Widmanstatten | 10 | 9.57 | 178 | 443.08 |
| | Center: Ferrite - Pearlite | 11 | 8.07 | 158 | 375.88 |
| | Bottom: Ferrite - Pearlite | 11 | 7.39 | 161 | 385.96 |

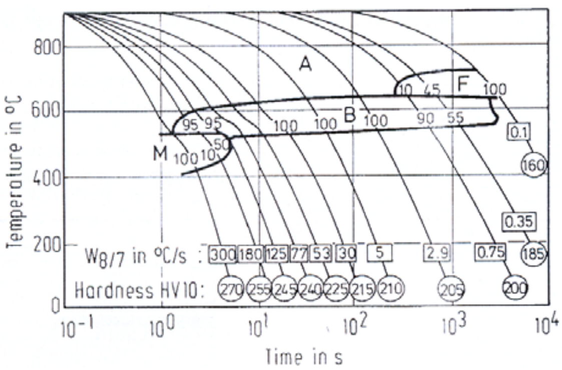



Fig. 5 The transformation behaviour for simulated HAZ of heat treated HSLA steel [11]