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How the Laser Beam Energy Distribution Effect on Laser Surface Transformation Hardening Process; Diode and Nd:YAG Lasers

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Abstract:

The laser surface transformation hardening (LSTH) of AISI 4130 steel by 1600 W high power diode laser (HPDL) and 700 W Nd:YAG lasers were investigated in this present study. The distribution influence, and the lasers beam shape; Top-hat in the HPDL and Gaussian distribution in the Nd:YAG laser, have been studied on the geometrical dimensions, and micro-hardness in hardened area (i.e.; depth, width, and angle of entry of hardened profile), micro-hardness deviation (MHD) from the row steel in geometric dimensions, and the ferrite's percentage in hardened layer center. Microstructure evaluation of the laser hardened areas were performed by FE-SEM and optical microscopy. Based on the results, maximum hardness was created with the HPDL, and the geometrical dimension was more than the Nd:YAG laser. Also, MHD, and minor phase of ferrite in the HPDL laser surface hardening than the hardened layer in Nd:YAG laser, which is related to the higher laser absorption. Results show that, the hardened zone of HPDL is about 698 HV0.1 with 1.02 mm depth, while for Nd:YAG laser is about 698 HV0.1 with 0.98 mm depth. Comparing the results with the furnace hardening heat treatment (FHT) demonstrated that the hardness in diode laser and Nd:YAG laser hardening are 1.38 and 1.22 times of the hardness in FHT, respectively.

Keywords: Industrial lasers; Laser surface treatment; AISI 4130 low alloy carbon steel; Beam shape

1. Introduction

Laser Surface transformation hardening (LSTH) is an indispensable last step in the manufacture of stamping and forming acts. LSTH is one of the necessary and new fashioned industrial activities which apply high energy density of the laser beam with very quick heat on the top of the work-piece at above the austenitic temperature of the alloy steel [1]. Heat input is a crucial factor in the LSTH. Increasing the heat input in the specific area leads to the thermal energy increases, and the surface phase of steel will be provided for austenitization. When laser transfer from the top of a surface, the phase was cooling and the martensite was formed [2]. The brilliant advantage of the LSTH rather than traditional methods is quickly, and in a short time, can do all crucial functions that need for surface hardening [3]. Figure 1 depicts the AISI 4130 hardened of the LSTH.



Figure 1. AISI 4130 hardened of the LSTH [4]

In LSTH, after the quenching (quenched in the air), a significant amount of the hardened layer will be created [5-7]. LSTH needs the laser and the CNC devices for control and organization the directions of a process [8-11]. As a matter of fact, the LSTH is very suitable for quick and accurate objects that the surface hardened type is needed [12-16].

Klocke et al. [17] investigated the HPDL for LSTH with a laser power of 650 W on 42CrMo4 steel. The main goal of the research was to increase the beam intensity of the HPDL by changing the laser inputs (such as power and CNC scanning speed). Maximum microhardness for the 42CRMo4 steel was measured to 700 HV with a depth of 0.5 mm. Haug et al. [18], by utilizing the HPDL with 300 W CW power could study the LSTH of the 100Cr6 steel to increase the micro-hardness. Pantelis et al. [19], investigated the surface properties of the CK60 hardened steel by using an industrial CW laser (CO₂) with a 3 kW laser power. In their article, the wear and corrosion behavior of the samples after LSTH was examined. Katames et al. [20], studied the LSTH without melting of 615CrNi steel by performing a CO₂ laser with a 3 kW laser power while all of the workpieces were coated with graphite (black cover) to enhance absorption. A considerable increase in the surface micro-hardness about 2.5 times of the row steel with 0.6 mm and without the surface defects. Sun et al. [21] accomplish an investigation on the simulation of the LSTH of the 42CrMo steel by using an industrial Nd:YAG laser with Gaussian beam shape by introducing a new model for simulation of the heat input to the surface by FEM. The simulation results were utterly correspond with the experimental values. Ehlers et al. [22] carried out the LSTH by performing a 2 kW HPDL to achieve the 740 hv micro-hardness and 1.9 mm in depth. Li et al. [23] conducted a study on the LSTH of AISI 1045 apply industrial lasers: HPDL with 3.5 kW and a 15 kW CO₂ laser. The results showed that the geometric dimensions of hardened cases by performing the HPDL are much higher than the CO₂ laser one. The maximum micro-hardness, geometric dimensions (depth and width), and also the angle caused by the curvature of the hardened zone, were investigated by using the response of the surface method statistical method. Benyounis et al. [24] investigated the coating evaluation study on 300 series stainless steel. DOE of design of experiment method is used in this study and optimum conditions provided for the laser coating process. Moradi et al. [25] investigated the comparison study of HPDL and Nd: YAG laser by LSTH on AISI 410. Fahdil iidan et al. [26] investigated a comparative study of LSTH by CO₂ laser Cr steels. Also, the comparative study on the influence of the beam shape was investigated by Saftar et al. [27] on LSTH. A FEM such as ANSYS software has been presented to analyses the effect of various beam shapes on LSTH. Moradi et al. [28] investigated the LSTH of AISI 4130 by using the RSM method. Results indicated that the RSM modeling on the variables is a suitable method for studying the effects of the LSTH by HPDL. ABAQUS software is the superb route for simulation of the laser material process specific LSTH. By the FEM of the Nd: YAG heat source and the heat input equation was evaluated by Jahromi et al. [29].

Notwithstanding various studies on the LSTH, the comparison of HPDL and Nd:YAG laser in LSTH of AISI 4130 has not been investigated before. Herein, effects of the laser surface hardening by performing these two applied industrial lasers are compared and studied on the hardening characteristics; the hardened profile, such as the hardened depth profile, the hardened width profile and the angle of entry profile, the micro-hardness distribution in the depth and width of hardened areas, the MHD, the microstructure, and the ferrite phase percentage in the structure of the hardened zone of AISI 4130 low alloy steel. Finally, the LSTH samples of both lasers are compared with FHT.

2. Experimental Work

The AISI 4130 steel is known as low alloy carbon steel with the chemical composition that depicts in Table 1. The chemical composition was evaluated by the Quanto-meter (ARL-3460 made in Switzerland) at a temperature of 23°C and a moisture content of 33%. The samples were prepared from round bar steel with 10 mm thickness and 65 mm diameters by using the traditional machining. The LSTH of the AISI 4130 was carried out with 1600 W HPDL with continuous wave (CW) and 700 W Nd:YAG pulsed-wave solid-state lasers that used in industrial applications.

Table 1 AISI 4130 chemical composition (Wt. %)

| Element Name | С | Cr | Мо | Si | Mn | Ni | Cu | Al | V | Р | S | Fe |
|-----------------|------|------|------|-----|------|------|------|-------|-------|-------|------|---------|
| Weight percent | 0.25 | 1.01 | 0.25 | 0.3 | 0.87 | 0.05 | 0.06 | 0.024 | 0.012 | 0.016 | 0.03 | Balance |

Table 2 and Table 3 illustrate the inputs and outputs of the LSTH of the AISI 4130 steel by using HPDL and Nd:YAG solid-state laser, respectively. The maximum heat input in hardened cases by HPDL and Nd:YAG lasers are $280 \frac{j}{mm}$ and $180 \frac{j}{mm}$, respectively. The range of HPDL parameters are; laser power (P) of 1200 to 1600W, focal plane position (FPP) of 60 to 80 mm, and scanning speed (S) of 3 to 6 mm/s. The wavelength of the HPDL is 808 nm, and its color is invisible, and also, the FPP is a rectangle with 8 × 1.5 mm dimensions.

| | Inpo (Co | ut varial ded valu | bles ues) | | - | | | Outj | put respo | onses | | | |
|-----------|--------------------------|-----------------------|------------------------------|-------------------------------------|---------------------------------|-----------|----------------------|------------------|---------------------|----------------------|--|--------------|--------------|
| Sample No | Scanning Speed (mm/s) | Laser Power (W) | Focal Plane Position (mm) | Max Depth of hardened layer (mm) | Width of hardened layer (mm) | Angle (°) | Micro Hardness (h v) | Average Hardness | Ferrite percent (%) | Interaction Time (s) | Area of FPP on steel (mm ²) | MHD in depth | MHD in width |
| 1 | 4 | 1500 | 65 | 0.94 | 9.3 | 10.82 | 724 | 553 | 0.22 | 0.64 | 25.3 | 48074 | 95475 |
| 2 | 7 | 1400 | 70 | 0.22 | 8.86 | 3.04 | 401 | 388 | 14.21 | 0.5 | 42.7 | 2340 | 5889 |
| 3 | 5 | 1400 | 70 | 0.47 | 9.82 | 5.95 | 665 | 514 | 0.47 | 0.7 | 47.7 | 22045 | 52629 |
| 4 | 5 | 1400 | 60 | 1.02 | 9.78 | 13.02 | 792 | 643 | 0.18 | 0.3 | 12 | 70987 | 111356 |
| 5 | 5 | 1400 | 80 | 0.30 | 9.97 | 4.29 | 433 | 391 | 9.4 | 1.13 | 89.3 | 2000 | 9972 |
| 6 | 6 | 1300 | 75 | 0.27 | 8.73 | 4.06 | 421 | 392 | 9.62 | 0.8 | 64.2 | 9378 | 9063 |
| 7 | 6 | 1300 | 65 | 0.42 | 9.03 | 7.02 | 642 | 536 | 0.6 | 0.4 | 25.3 | 7363 | 49463 |
| 8 | 4 | 1300 | 75 | 0.39 | 9.24 | 5.24 | 634 | 442 | 0.62 | 1.16 | 64.2 | 1686 | 33065 |
| 9 | 4 | 1300 | 65 | 0.52 | 9.10 | 6.78 | 698 | 525 | 0.27 | 0.6 | 25.3 | 16359 | 60455 |
| 10 | 6 | 1500 | 65 | 0.50 | 9.27 | 6.57 | 681 | 517 | 0.41 | 0.4 | 25.3 | 33246 | 59665 |

Table 2. Inputs and outputs HPDL of the LSTH of the AISI 4130 steel

As shown in Table 3, the ranges of the input variables for Nd:YAG solid-state laser are: mean laser power (130 - 155 W), scanning speed (0.2 - 1 mm/s), Pulse width (15 - 20 ms), while the pulse frequency is considered fixed at 15 Hz and FPP of 8 to 11 mm. The pulsed Nd:YAG laser LSTH experiments were used by a 700W average laser power. It is crystal clear that any optional value of pulse frequency and pulse energy is not available, while the average power of the laser could not exceed 700 W. Three lenses (75mm focal length) is used in the focusing optical system, and the minimum spot size is 250mm. In order to measure the laser beam energy and the power in each experiment in both types of the lasers, LA300W-LP joule meter, and 5000W-Lp Ophir power meter is used. The hardened cases were cut after the LSTH, then mounted by resin. Micro-hardness was evaluated by the micro-indentation device (BUEHLER, MH-73-01 made in the USA) from the hardened profile.

| | Input Variables | | | | | Output Responses | | | | | | | |
|----------|----------------------------|----------------|------|--------------------|-----------------------------|----------------------|------------------------------|-----------------------|------------------------------|---------------------------|-----------------|-----------------|--|
| Sample N | Focal Plane Dreition | Pulse width | (ms) | Laser Power (W) | Scanning Speed (mm/s) | Depth of hardness | Width of hardness (µm) | Angle of entry (°) | Maximum Hardness (h v) | Ferrite percent (%) | MHD in depth | MHD in width | |
| 1 | 11 | 15 | | 130 | 1 | 71 | 1821 | 4.37 | 397 | 14.05 | 1592 | 21474 | |
| 2 | 8 | 15 | | 130 | 1 | 980 | 1774 | 53.3 | 698 | 0.25 | 19501 | 19768 | |
| 3 | 9 | 15 | | 130 | 1 | 360 | 1805 | 21.67 | 690 | 0.32 | 17040 | 21115 | |
| 4 | 9 | 17 | | 135 | 1 | 271 | 1768 | 17.07 | 681 | 0.4 | 9242 | 7848 | |
| 5 | 11 | 17 | | 135 | 1 | 100 | 1837 | 6.14 | 548 | 1.07 | 1932 | 22042 | |
| 6 | 11 | 20 | | 155 | 1 | 141 | 1862 | 8.63 | 566 | 0.92 | 4730 | 26435 | |
| 7 | 11 | 17 | | 135 | 0.5 | 143 | 1897 | 8.35 | 585 | 0.81 | 5520 | 34454 | |
| 8 | 11 | 20 | | 155 | 0.5 | 157 | 1915 | 9.1 | 665 | 0.47 | 7300 | 37136 | |
| 9 | 11 | 20 | | 155 | 0.2 | 193 | 2284 | 9.63 | 673 | 0.43 | 8563 | 43202 | |
| 10 | 11 | 18 | | 140 | 0.5 | 146 | 1936 | 8.41 | 599 | 0.76 | 6430 | 39079 | |

Table 3. Inputs and outputs Nd: YAG laser of the LSTH of the AISI 4130 steel

The samples were etching the Nital reagent, (Ethanol 5 cc, and Nitric acid 95 cc) and prepared for microstructure analysis. Leica MEF 4A optical microscopy (OM) with 50-100X magnification and the ImageJ software were used for measuring the geometry features of the hardened layer. Figures 2, and Figures 3 show the LSTH samples for HPDL and Nd:YAG lasers, respectively. Optical microscopy (OM) and TESCAN MIRA3 FE-SEM were applied for investigating the hardened layer. The ferrite phase percentage was evaluated by Celemex software in hardened zones.



Figure 2. Hardened area for LSTH by the HPDL



Figure 3. Hardened area for laser transformation hardening Nd:YAG solid-state laser

3. Comparing the Nd:YAG and HPDL beam in materials processing

In this research, all conditions are the same for both lasers. The major difference in this research is the type of laser beam. For better understanding of the laser beams used on this study, Nd:YAG laser and HPDL beam, a comparison of these two types laser could help for better discussion of their effect in the LSTH. The two effective points in the absorption are the shape of the laser energy distribution and the laser wavelength [30]. For black pieces, the absorptivity (A) which shows in Equation 1 [31 & 32]:

R is the reflectivity beam of the pieces. In Figure 4, the reflection rate for some famous lasers is given in terms of their wavelengths interact with different materials. As shown in Figure 4 in lasers with shorter wavelengths, the reflectivity of the laser is reduced. For our two types of laser in this research, HPDL beam with a longer wavelength (0.808 μ m) absorbs more thermal energy than 1.064 μ m wavelength beam of the Nd:YAG laser.



Figure 4. The reflection curves of different lasers on the material relative to the wavelength [30]

Figure 5 depicts the schematic of the laser beam distribution of two mentioned lasers types [33-35]. Figure 5-a & c are shown the distribution of the HPDL. Also, Figure 5-d & f are shown the Nd:YAG laser's beam energy. The shape of a Top-Hat energy in the HPDL and the shape of Circular Gaussian energy in Nd:YAG laser are shown in Figure 5-d & e, respectively.



Figure 5. The laser beam energy distribution a) distribution of the HPDL beam energy b) HPDL beam shape c) rectangular plane position d) Gaussian distribution of the Nd:YAG laser beam energy e) Nd:YAG laser beam shape f) circular spot position [4]

4. Results and discussion

In this study, the effect of the HPDL and Nd:YAG lasers on the LSTH of AISI 4130 low alloy steel has been studied. For this purpose, the distribution of micro hardness in geometric dimensions of the hardened zone, microstructure, MHD in width and depth, ferrite percentage, and also the comparison of FHT (conventional processes) and LSTH of AISI 4130 steel was investigated.

4-1 The hardened area micro-hardness distribution

Micro-hardness distribution for the HPDL and the Nd:YAG laser after LSTH of AISI 4130 are illustrated in Figure 6. As shown, Figure 6-a depicts the micro-hardness trends of the samples 5 and 6 by the HPDL. The compression between the Figure 6-b (samples #8 and #6 by Nd:YAG laser), and the Figure 6-a are shown that the micro-hardness in HPDL is greater than Nd:YAG laser of LSTH samples.



Figure 6. The hardened area micro-hardness distribution in depth by performing a) HPDL b) Nd:YAG laser

Figure 6 shows well that surface hardness increases as a result of the LSTH, by moving from the surface of the hardened area to the row steel, the hardness slowly reduces until it reaches to the row steel hardness. This decreasing is because of decreases in laser energy transferred to the steel little by little, and then the penetration will be limited as well.

The width hardened profile for HPDL and Nd:YAG laser depicts in Figure 7. As seen the Figure 7, the maximum micro-hardness throughout the top of the surface is reported for HPDL in the LSTH. The HPDL samples such as #5 and #6 the micro-hardness are measured about 800 hv, whereas the maximum micro-hardness for selected samples Nd:YAG laser (#8 and #9) are evaluated about 700 hv.



Figure 7. The hardened area micro-hardness distribution in width by using a) HPDL b) Nd: YAG laser

Heat input on samples and absorption energy are two effective factors in LSTH. For many of the Laser applications, the heat inputs were shown by the following equation (Equation 2 [12]):

Heat Input =
$$\frac{Power}{Velocity}$$
 (2)

When the heat input increases, the surface's temperature reaches the austenitic temperature, and austenite particles are being created. Then, after the LSTH surface is being quenched by air and martensitic phase is formed. Also, with higher austenitic temperature, more ferrite particles are dissolved, and the amount of this phase has been reduced. While ferrite particle isn't a rough phase, its presence in the hardened case, decreases the micro-hardness. The absorptivity and the physical properties of HPDL and Nd:YAG lasers of the AISI 4130 is shown in Table 4.

| Physical & | Density, | Thermal Conductivity, BTU/hr/ft/(W/m/k) | Modulus of | Specific, Heat, | Absorptivity,% [28] | | |
|------------|----------------------|--|------------|---------------------|---------------------|-------------|--|
| properties | $lbs/in^3(g/g/cm^3)$ | | ksi. (Mpa) | BTU/lbs/°F(kj/kg/k) | Nd:YAG laser | Diode laser | |
| AISI 4130 | 7.85 | 42.7 | 205 | 0.477 | 28-31 | 45 | |

Table 4. Absorptivity and Physical properties of 4130

Increases in transferred laser energy lead to a higher temperature in the material, which causes a wider and deeper hardened zone, and also the surface hardness will be increased in the HPDL than the Nd:YAG laser.

4-2 The hardened profile geometrical dimensions

Figure 8 shows the profile dimensions of the hardened zone of AISI 4130 by using the HPDL and the Nd:YAG laser.

| 4 | Hardened Width | |
|----------------------------------|----------------|-------------------|
| β | and S. Th | Hardened Depth |
| Angle of Entry of Hardened | | * |
| Thurdenfeu | i en este | 2 <u>00 µm</u> |

Figure. 8 Geometrical dimensions (depth, width, and angle of entry of hardened profile) of the hardened area of AISI 4130

The geometric dimensions of the AISI 4130 by HPDL are greater than Nd:YAG laser (see Table 2 and 3). The heat input has an effective role in the LSTH and increases this factor lead to higher micro-hardness. Based on the previous information about heat input and absorptivity, the HPDL has a wider width and a deeper depth than Nd:YAG laser in LSTH (this phenomena is deeply explained in section 3). The laser beam shape distribution is another factor in which the diode laser is rectangular, and the Nd:YAG laser is Gaussian. As seen in Figure 7, the HPDL cover a wide zone of the top of the samples than the Nd:YAG laser. Thus it is another reason for having a greater hardened area in the HPDL case. The laser beam in the center of

the affected area for two lasers is heater than beside of that, and also, by getting away from the center of the beam, the energy intensity of the laser beam decreases [37]. Therefore, the hardness in the center of affected zone is higher than its corners. And because of these explanations, the shape of the hardened zone is like a lunular nail that has a crescent shape. Figure 6 shows the comparison of the micro-hardness distribution of AISI 4130 by performing the HPDL and Nd:YAG lasers in depth of the hardened area. The specific beam shape (rectangular) of the HPDL creates a more effective area to thermal energy and leads to higher penetration than Nd:YAG laser.

4-3 The hardened area microstructure comparison

In the LSTH, because of the time of dissolve is very limited, the ferrites in the row steel aren't changing another phase, so the process is incompletely performed. The ferrite particles can be completely dissolved and reached to full martensitic microstructure by handle the heat input value [36]. The AISI 4130 microstructure of the row steel is depicted in Figure 9.



Figure 9. The AISI 4130 microstructure of the row steel

Figure 10 illustrated the profile of microstructure after the LSTH by performing the HPDL and Nd:YAG lasers. Ferrite and martensite particles are visible. Due to the high velocity of the cooling known and the limited time to dissolve ferrite, ferrite particles are solved incompletely and remains in the martensite [37, 38].



Figure 10. a) Nd:YAG LSTH, b) Nd:YAG LSTH in 100 kx magnified, c) LSTH microstructure of the HPDL, d) LSTH microstructure of the HPDL in 100 kx magnified

For further and precise analysis, FE-SEM images were taken by the microstructure of the hardened samples and the row steel. Figure 11 shows the FE-SEM figures of the hardened zone and row steel. The ferrite phase in the martensite phase are entirely clear that Figure 10-c. Based on Figure 11-a & b, and compare them with the Figure 10-c & d, it is clear that the grain size of the Ferrite phase in the HPDL is more tinier than the analogous sample of Nd:YAG laser. As can be seen in Figure 11-a & b, and also in Figure 10-c & d, the Ferrite grains in the HPDL sample are tinier than the Nd:YAG laser sample.



Figure 11. FE-SEM of AISI 4130 a) Row steel microstructure b) Nd:YAG laser hardened sample microstructure c) Retained austenite d) HPDL hardened sample microstructure

4-4 Micro-hardness deviation from the row steel (MHD)

Equation 3 shows the evaluated factor which is named MHD:

MHD=
$$\sum_{i=1}^{n} \frac{(x_i - x_{b.m})^2}{n}$$
 (3)

Where x_i is the micro-hardness of hardened zones, $x_{b.m}$ is the micro hardness of the row steel, and n is the number of zones that their micro-hardness is tested. In this research, n is 15, and $x_{b.m}$ is equipollent to 256 Hv (micro-hardness of row material). Calculated MHD values for all samples are presented in Table 2 and Table 3. Maximum hardness by HPDL and Nd:YAG laser is 792 HV and 698 HV, respectively. By comparing the both laser samples, a higher amount and trend of MHD of both in geometrical dimensions in HPDL samples is seen (Figure 12). The reason for this difference could be explained by the phenomena which is explained in section 3. Distribution, the beam shape (rectangular and Gaussian), and also, the laser absorptivity are the main reasons for comparing the behavior of these two types of lasers.



Figure 12. Diagram of Comparison of MHD in HPDL and Nd:YAG lasers a) MHD in hardened zone depth profiles b) MHD in hardened width profiles

4-5 The hardened zone ferrite phase percentage

The outputs results from Clemex software on ferrite phase percentage thorough the hardened cases indicated that mico-hradness of LSTH is affected by the types of the lasers. The ferrite phase is known as the soft phase rather than the martensitic phase. So when the ferrite phase increases in each of the samples, the hardness decreases. Figure 13 illustrates the amount of the ferrite phases in HDPL and Nd:YAG samples. The reason for the higher ferrite phase in the HPDL is related to input energy absorbed by the steel surface more than Nd:YAG laser.



Figure 13. Diagram of Comparison of ferrite grain in the LSTH samples

4-6 Comparing the FHT and LSTH

In this part, comparative research on the FHT and LSTH by using two lasers are debated. Microstructure and micro-hardness of the two types hardening have been shown, and the Cycle of FHT in Figure 14 are illustrated.



Figure 14. The Cycle of FHT of AISI 4130 [39]

Sample of steel was preheated at 540 $^{\circ}$ C for one hour and then heated to a temperature of 899 $^{\circ}$ C with a rate of 73 $^{\circ}$ C / hr. It was kept at this temperature for 11 minutes. Then it was quenched with three cooling methods (air, oil and water). Table 5 indicates the comparison of the hardness results of the FHT and the LSTH. Because of the surface quality without any defects, the water and air quenched samples were rejected. In the quenched sample, many cracks was observed, and the sample was quenched in the air, the micro-hardness was very low, whereas the oil sample has a suitable quenching condition (surface quality and ranges of micro-hardness) with a 572 Hv micro-hardness. So the micro-hardness range with the LSTH method (673 Hv) is 1.18 times than the FHT.

| Heat treatment cycle | furnace hardening | LSTH |
|----------------------|-------------------|--------|
| Quenched in oil | 572 Hv | - |
| Quenched in water | 681 Hv | - |
| Quenched in air | 421 Hv | - |
| LSTH (#9 table 2) | - | 673 Hv |

Table 5 LSTH and 3 types of quenching after FHT micro-hardness

Quenching in the oil without any crack after the visual inspection, was a suitable sample for comparing to LSTH. The micro-hardness in the oil quenching sample is evaluated about 572 HV. Table 5 illustrates that the micro-hardness of the samples of the both lasers have had more mico-hardness than FHT sample. Figure 15 presents the microstructure image of the FHT sample cooled in oil. As seen according to metallographic images the martensite phase in the FHT quenched in oil sample (Figure 15) is more uniform in comparison with the laser hardened samples (Figure 10-a and Figure 10-d) while the base phases of AISI 4130 is ferrite-perlite. Also, there is more unsolved ferrite phase in the FHT case.



Fig. 15 a) FHT hardened microstructure that quenched in oil by the magnitude of 200 b) FHT hardened microstructure that quenched in oil by the magnitude of 500

5- Conclusions

In this research collection, a comparison investigation on LSTH of AISI 4130 low alloy steel was conducted by 1600 W HPDL and 700 W solid-state Nd:YAG laser. Based on the results of the researches, the following conclusions can be defined:

- 1. HPDL creates a wider, and higher surface hardness than the Nd:YAG laser because of the higher laser absorption coefficient in the HPDL, which caused by shorter wavelength in Nd:YAG solid-state laser. In the HPDL, more heat input transferred to the surface, and the temperature of the austenitic phase increases.
- 2. The uniform trends of MHD from the hardening zone was observed in the samples were hardened by HPDL. That is because of the more width and depth hardened zones are generated by HPDL rather than the Nd:YAG laser.
- 3. Based on the particular shape of the HPDL beam, the affected area that hardened by the HPDL is more wider and deeper in geometrical dimensions of the hardened zone of AISI 4130 than Nd:YAG solid-state laser which has a Gaussian energy distribution.
- 4. The maximum microhardness value of AISI 4130 obtained in diode laser hardening is 792 HV with 1.02 mm depth and in Nd:YAG solid-state 700 W LSTH is 698 HV with 0.98 mm depth which are 1.38, and 1.22 times the hardness of FHT (572 HV), respectively.
- 5. The amount of ferrite phase in the FHT samples are more than from HPDL and Nd:YAG lasers hardening. This is due to the high concentration of energy and the increase in temperature at a specific point, which completely solves the ferrite phase.

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