Laser transformation hardening of metal sheets under air and water environment

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KEYWORDS

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Transformation Hardening,
Water Environment,
Mild Steel,
Micro-Hardness.

ABSTRACT

Laser transformation hardening is a type of surface treatment process for localized hardening of material surface with high control on hardening depth. Further, laser hardening is a self-quenching process with high cooling rate. The current study presents the laser transformation hardening of mild steel under dry and wet environments with single and multi-passes, where the wet environment was created by providing a water-jet parallel to the work-piece surface. The main objective is to study the effect of wet environment on the hardness values and hardening depth in the modified zone due to enhanced cooling. Further, the effect of process parameters, like scan speed, laser power and number of passes on the enhancement of the hardness is also studied. Results indicate significant improvement in the micro-hardness of the treated surface in a water environment under both single and multi-pass conditions.

1. Introduction

Laser surface transformation hardening is a kind of surface heat treatment process, which uses a laser beam for hardening the surface of the work-piece in a localized region, and the rest of the work-piece act as the heat sink leading to self-quenching (Nath & Sarkar, 2018). High intensity of laser and very high processing speed results in rapid heating and cooling in laser hardening, which leads to steep temperature gradient, resulting in high cooling rate and thus provides better control on the hardening depth and surface properties (Sarkar et al., 2016; Roy & Manna, 2001). The main characteristic of transformation hardening is the conversion of austenitic phases to martensitic phases due to high quenching rate without melting the surface and is generally done in low alloy steels and medium carbon steels to enhance the properties of suface such as hardness, wear and corrosion resistance, fatigue strength etc. without affecting the bulk properties such as toughness and ductility.

Roy and Manna (2001) performed laser surface hardening (LSH) and laser surface melting on austempered ductile steel to enhance surface wear properties, and found LSH to produce higher hardness and less susceptible to crack formation. Lee et al. (2009) reported an improvement of surface hardness of AISI H13 tool steel by approximately two times after treating by a 200W fibre laser. Salleh et al. (2020) used fibre laser to do LSH of mild steel, and reported a maximum average surface micro-hardness of 281.72 HV at 21 W laser power and 40 mm/s scan speed. Sarkar et al. (2016) performed LSH experiments using a fiber laser on steel having low carbon percentage consisting 0.05% and 0.07% carbon, and reported an increase in average micro-hardness from 120 to 217 HV for 0.05% carbon steel, and from 160 to 280 HV for 0.07% carbon steel. Telasang et al. (2015) studied the effect of laser parameters on the microstructure along with the wear and corrosion resistance of AISI H13 tool steel, and found a significant improvement in the surface micro-hardness ranging from 670-810 VHN as compared to substrate having hardness 500 VHN. They also found improvement in corrosion resistance and wear as a function of laser fluence. Lu et al. (2021) studied the impact of multi-pass laser hardening of AISI 4140 steel on the hardness and grain size. Multi-pass was found to result in homogenization of carbon distribution. Further, grain size was found to reduce with distance to the surface due

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to inhomogeneous temperature field in depth and different degree of carbon diffusion.

Few researchers have explored the effect of wet environment in laser surface treatment for further improvement of surface properties. Maharjan et al. (2019) performed underwater laser hardening along with laser hardening in argon environment for two types of bearing steels (50CrMo4 and AISI 52100) using a fiber laser. With hardening in water environment, they obtained an average surface hardness of around 1.1-1.2 fold of that obtained in dry environment. However, the hardening depth was significantly smaller (0.2-0.33 times) in the instance of underwater laser hardening compared to that obtained with hardening in conventional argon gas environment. Sakate et al. (2021) investigated the underwater wet laser welding of steel sheets with the assistance of water jet and found that due to forced heat convection, the cooling rate was enhanced which resulted in a more refined microstructure. However, there is lack of work on laser surface treatment in wet environment. Further, the laser processing in water results in some extra loss of laser power due to water environment. The significant loss mechanisms are reported to be as the laser absorption in water, water vapour formation at the processing zone resulting in scattering of laser beam as well as the convective heat transfer in case of flowing water (Mullick et al., 2016).

The current work investigates the laser transformation hardening of mild steel plates under dry and wet environment. In dry environment the hardening is done in argon environment to avoid oxidation, whereas the wet environment was created by providing a water flow parallel to work-piece to generate a thin laminar flow of water layer of depth 1-2 mm. The micro-hardness of the treated surface was analysed to study the effect of wet environment along with the other process parameters (laser power, scan velocity and line energy) and number of passes. Further, fast laser heating and cooling generally results in distortion or bending of work-piece, specifically in case of thin section (Lambaise, 2012; Bajpei et al., 2017) because of the development of high thermal stress due to steep temperature gradient. When the thermal stress exceeds the elastic limit of material, it leads to permanent deformation, which is represented in the form of distortion. Therefore, the effect of wet environment on the amount of distortion (bending angle) of thin steel sheets during surface heating is experimentally analysed to understand the effect of cooling for minimizing the same.

2. Experimental Details

The experiments on laser transformation hardening is carried out on mild steel (AISI 1020) plate using a CW mode Yb-Fiber laser with maximum laser power of 240 W and laser spot diameter of ~900 µm. The elemental composition of the work-piece material is given in Table 1. In the current study, laser hardening in dry environment is conducted in argon atmosphere, which was provided as shielding gas. Whereas, the wet environment was introduced by providing a water-jet parallel to the work-piece creating a 1-2 mm thick water layer over the surface. A nozzle with a cross-sectional area of 7×2.5 mm was used to provide a flatter water-jet with a velocity in the range of 1.75 m/s. The experimental set-up for the wet environment hardening process has been shown in Fig. 1. The water circulation was done in a closed channel with the help of a centrifugal pump.

The main objective of the experiment is to study the effect of cooling rate on surface hardening in both air and water environment, as the surface hardness depends on the type of micro-structure that is developed which in turn is dependent on the temperature rise at the surface and the cooling rate. This is controlled by the laser interaction

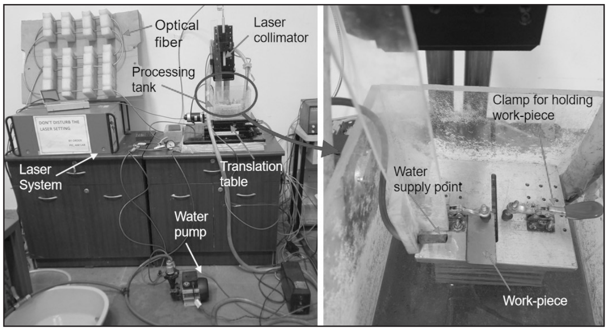

Fig. 1. Experimental set-up for laser surface treatment in wet environment.

Table 1
Elemental composition of the work-piece material.

Element	C	Si	Mn	S	P	Fe
Wt%	0.16-0.18	0.4	0.7-0.9	0.04	0.04	Bal

with the material, which is the function of the scan speed. Therefore, the effect of interaction time is studied under constant and variable line energy (heat flux) conditions. Further, there is a loss of laser energy during processing in water environment due to forced convection, formation of water vapour at the processing zone resulting in scattering of laser beam and absorption of laser radiation in water (Mullick et al., 2015). The amount of losses is calculated for the current experimental conditions (Mullick et al., 2015) and total loss comes in the range of approximately 40%. Based on the same, the amount of supplied power for experiments under wet environment has been modified. The range of process parameters for both the environmental conditions are listed in Table 2. The microstructure of the hardened layers was analysed using an optical microscope (Make: Leica), and the micro-hardness values were measured using Vickers micro-hardness tester (Model: ZwickRoell ZHVμ) with a load of 0.5 kgf and 10 sec dwell time.

Table 2
Range of experimental process parameters.

Process Parameters	Experimental Range	
	Dry Environment	Wet environment
Laser power (W)	70-90	115-150
Line energy (J/mm)	08-12	16-23
Scan speed (mm/min)	350-675	300-675
No. of passes	1-8 passes	

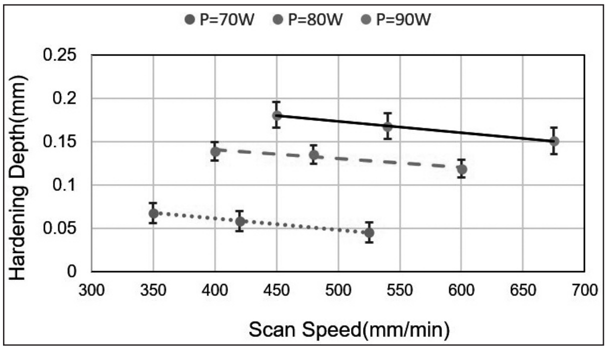

Fig. 2. Variation of hardening depth with scan speed and power under air environment.

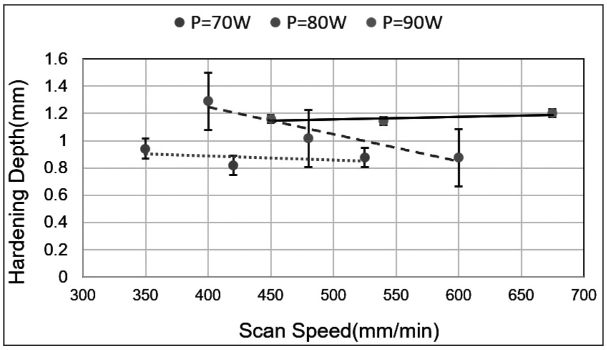

Fig. 3. Variation of hardening width with scan speed and power under air environment.

3. Results and Discussions

3.1. Effect of process parameters on hardening geometry

Fig. 2 and 3 represents the variation of hardening depth and hardening width respectively with respect to scan speed and laser power. Higher hardening depth and width are obtained at lower scan speed. This is due to the increase in interaction time with the laser font resulting in more energy input. Also, higher power results in an increase of hardening area as more heat is conducted to the material, hence resulting in an increased heat affected region.

3.2. Effect of process parameters on hardness under dry and wet environments

Fig. 4 presents the micro-hardness measured at the top surface of the hardened zone processed under dry (Fig. 4(a)) and wet environment ((Fig. 4(b)), measured from the centre towards the radially outward direction. Hardening in air was conducted at 80 W laser power, whereas in water environment the laser power was kept 135 W to compensate around 40% power loss in water. In both the environment, the hardness values are observed to increase with the increase in the scan speed, due to refinement of grain structure because of higher cooling rate. However, the hardness of the samples processed in water environment show a significant improvement (around 20-25%), specifically at higher scan speed. This may be because of further higher cooling rate in wet environment due to convective heat transfer.

Fig. 5 presents the effect of line energy (variable laser power and scan speed) on the micro-hardness measured at the top surface of the hardened zone processed under dry (Fig. 5(a)) and wet environment ((Fig. 5(b)), measured from the centre towards the radially outward direction. Hardening in air was conducted at a line energy of 10 J/mm with laser power ranging between 70-90 W, whereas in water environment the laser

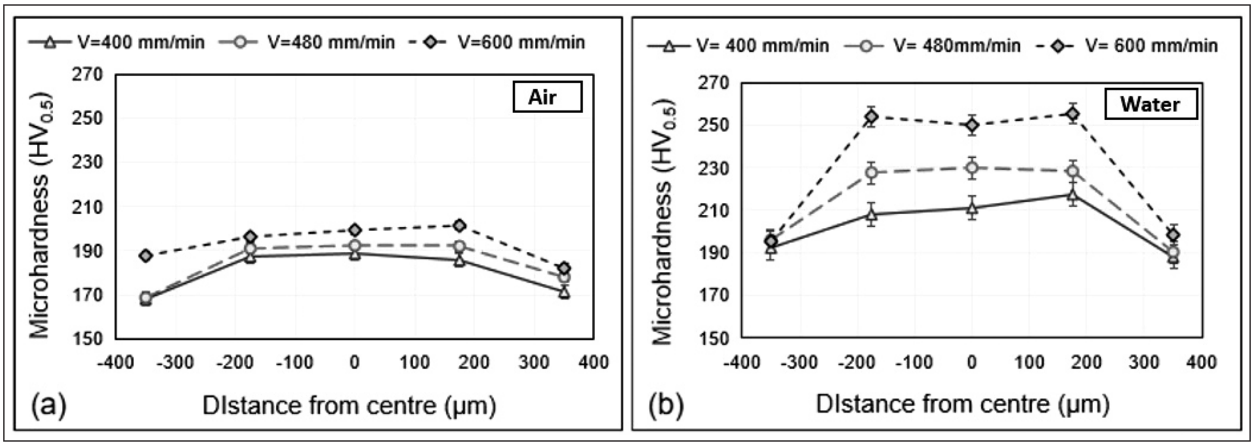

Fig. 4. Micro-hardness of the treated surface in case of (a) dry environment at 80 W power and (b) wet environment at 135 W power with variable line energy (variable scan speed).

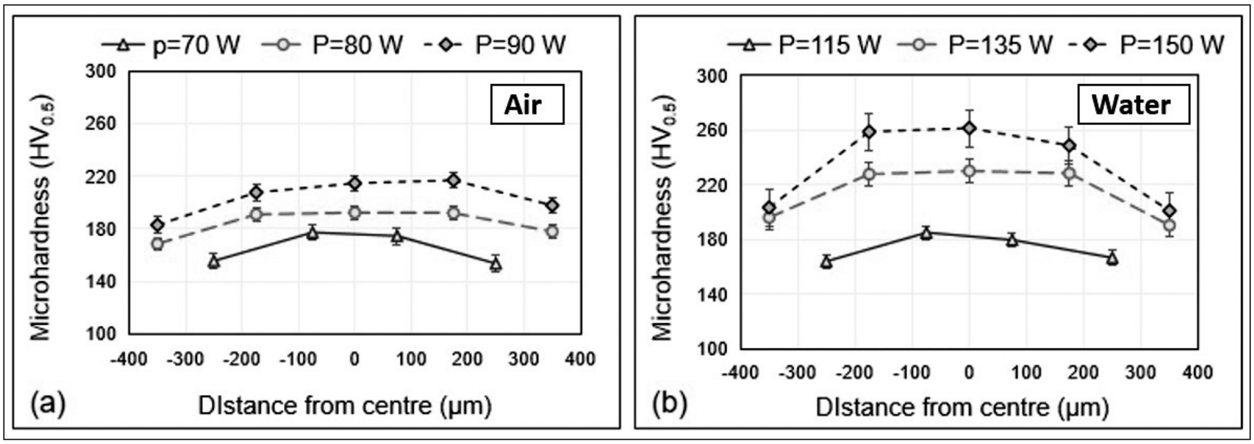

Fig. 5. Micro-hardness of the treated surface in case of (a) dry environment at 10 J/mm line energy and (b) wet environment at 16 J/mm line energy with variable laser power and speed.

power was kept in the range of 115-150 W with a line energy of 16 J/mm. In both the environment, it was observed that hardness values increases with the laser power, due to more heat input. The width of the hardened zone is found minimum with minimum laser power. Further, the hardness of the samples processed in water environment are significantly higher (around 20%), specifically at higher laser powers.

3.3. Effect of multi-passes on hardness under dry and wet conditions

The micro-hardness value at the surface is further observed to increase as the number of passes increases. Fig. 6 presents the change in micro-hardness with the increase in number of passes, both in air and water environment. All the runs are conducted at a scan speed of 400 mm/min, with 80 W and 135 W laser power for processing in dry and wet environment. A dwell time of 2 sec. is kept between two successive passes to allow the work-piece to come near to the room temperature and to avoid the effect of heat accumulation. Fig.6 indicates an increase in the surface hardness, however a saturation is found to reach beyond four number of passes. Application of multiple passes leads to more conversion of material to martensitic phases, however, after a sufficient number of cycles the cooling rate decreases to an extent that further transformation cannot take place. From a single pass to two pass a 20% increase in average hardness is observed while from two pass to four pass only an increase of 10% is seen. Whereas, no difference in the hardness values is observed beyond four passes. Further, the average micro-hardness obtained after any no of passes in case of wet environment is found to be around 20% higher compared to that obtained under dry environment.

3.4. Study the changes in microstructure

Fig. 7 represents the microstructural changes in the hardened zone processed under dry and wet environment with different number of passes. The

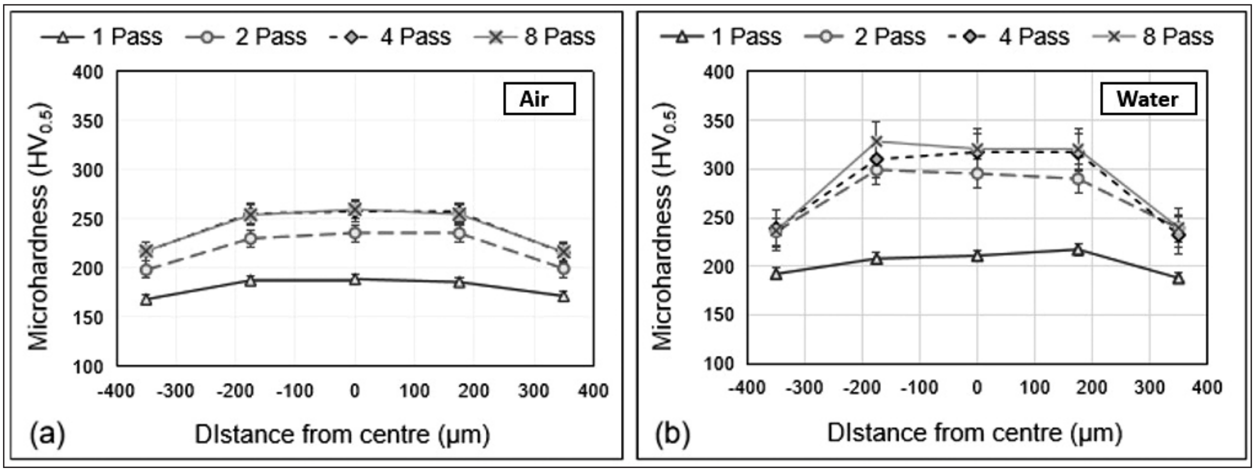

Fig. 6. Change in micro-hardness of the treated surface with different number of passes in case of (a) dry environment at 80 W power and (b) wet environment at 135 W power operated under constant scan speed of 400 mm/min.

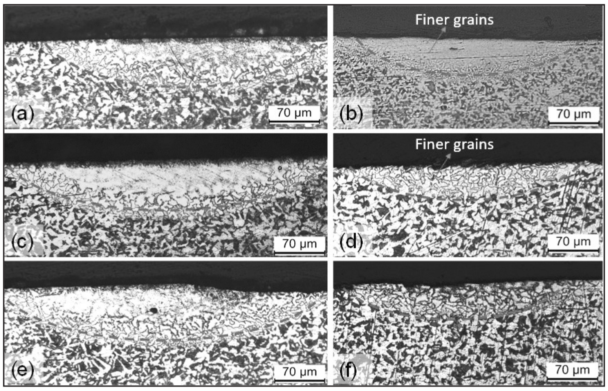

Fig. 7. Optical micro-graphs showing the microstructural changes along with the morphology of the cross-section of the laser hardened zone for (a), (b) two passes, (c), (d) four passes and (e), (f) eight passes, under the (a), (c), (e) dry condition and (b), (d), (f) wet condition. The hardening is done at a scan speed of 400 mm/min with laser power of 80 and 135 W for dry and wet condition, respectively.

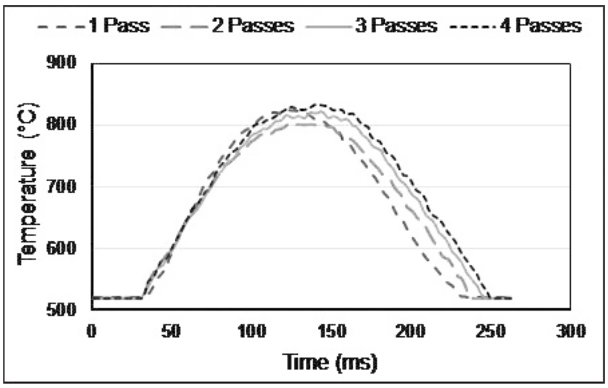

Fig. 8. Temperature history obtained by the IR-pyrometer showing the maximum temperature and cooling curve for different laser passes during hardening in dry environment at a scan speed of 400 mm/min and laser power of 80 W.

laser treatment is carried out at a scan speed of 400 mm/min with laser power of 80 and 135 W in dry and wet condition, respectively. The micrographs of the hardened zone in water environment indicates finer grains (Fig. 7(b), (d) and (f)) in comparison to that obtained with processing in dry condition (Fig. 7(a), (c) and (e)), which is expected to be the reason for higher hardness in wet environment (refer Fig. 2 and 3). However, the width and depth of the hardened zone is found to be more in case of dry environment. Also, the comparison of Fig. 7(a), (c), (e) and comparison of Fig 7(b), (d), (f) indicates no significant change in the microstructure of the samples with 4 and 8 passes (both in dry and wet environment), which may be the reason for no significant change in the micro-hardness after 4 passes (Fig. 6) in both the environments. Further, the thermal history captured by an IR-pyrometer (Make: Micro Epsilon, Model: CTLM-2HCF3-C3H, spectral wavelength 1600 nm) during the laser hardening in air environment for different number of passes are shown in Fig. 8, which indicates a minor reduction in slope of the cooling curve with the increase in no of passes, which may be one of the reasons for the saturation in the hardness beyond a number of passes.

3.5. Effect of environment on the distortion of the work-piece

Laser hardening generally develops a steep temperature gradient along depth, which results in high thermal stress, and finally results in distortion of work-piece, specifically in case of thin sections (Lambaise, 2012; Bajpei et al., 2017), which is highly undesired. This is due to the generation of thermal stress inside the material. However, the

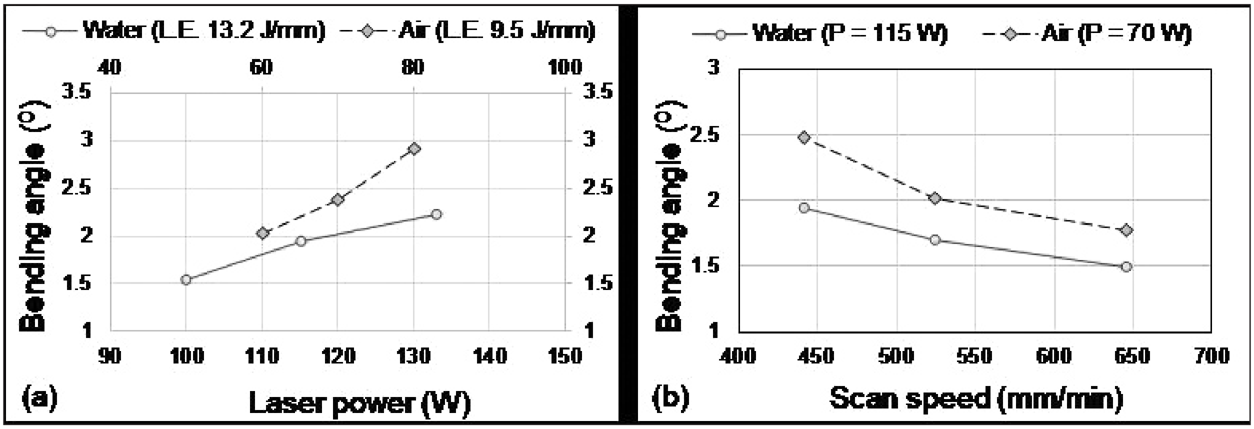

Fig. 9. The bending angle obtained during laser heating of 0.5 mm thick steel plate in dry and wet environment at (a) constant line energy with variable laser power and (b) variable scan speed (line energy) at constant laser power.

incorporation of wet environment is expected to result in lower distortion due to enhanced cooling because of forced convective heat transfer induced by flowing water. In case of distortion, the bending angle is inversely proportional to the sheet thickness (Vollersten, 1996; Rigas, 2020). So if thickness is increased more bulk material will be present to resist the deformation, Hence distortion will decrease and vice versa. Therefore, in this current work, a separate set of experiments is conducted to study the bending angle achieved during laser heating of thin work-piece (0.5 mm thick steel sheets) in air and water environment. The experiments were conducted at varying scan speed under constant and variable line energy (heat flux) in both the environments. However, the laser power in water environment is kept higher compared to that applied in dry environment considering around 40% laser power loss in water, which also results in higher line energy for processing in wet environment.

Fig. 9(a) shows the variation in bending angle with laser power under constant line energy (i.e. variable scan speed), whereas Fig. 9(b) shows the effect of scan speed on bending angle with laser power at a constant scan speed (i.e. variable line energy). Both the figures also present the variation in bending angle in dry and wet environments. In both the cases, it is observed that the bending angle increases with the increase in either laser power or line energy. Further, both the graphs indicate a reduction in the bending angle, in the range of 15-23% in case of water environment compared to dry condition due to the enhanced cooling.

4. Conclusions

The current work presents the laser transformation hardening of steel plates under dry and wet environment using a Yb-fiber laser system with ~900 µm spot diameter, to study the effect of enhanced cooling in wet environment on the micro-hardness values of the treated samples. This work also investigates the distortion of the work-piece which takes place during laser heating process. The following conclusions can be drawn from the current work:

1. The wet environment was introduced by providing a water-jet of speed in the range of 1.75 m/s parallel to the work-piece, creating a movable water layer of 1-2 mm thickness. The laser power during processing in water was kept higher considering around 40% loss of laser power due to convective heat transfer, scattering of laser light in water vapour formed at the processing zone and absorption of laser in water.
2. Micro-hardness values obtained with the treated samples under water environment were found to be higher, with approximately 20% more hardness with respect to that obtained in air environment, under the same set process parameters.
3. Higher number of pass results in an increase of micro-hardness of the treated surface irrespective of processing environment; however, the rate of increase gets reduced with the increase in the number of passes, and the values get saturated beyond four number of passes (under the current experimental conditions). In all the passes the micro-

hardness obtained for the samples treated in wet environment is found to be 20% higher than that obtained under dry environment.

4. The amount of distortion, i.e. bending of the sample due to thermal stress is found to reduce by 15-23% in case of processing in wet environment with respect to dry environment for 0.5 mm thick steel sheets.

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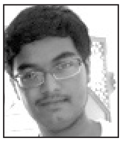

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