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Niroj Maharjan, Wei Zhou, Yu Zhou, Yingchun Guan, Naien Wu

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Comparative study of laser surface hardening of 50CrMo4 steel using continuous-wave laser and pulsed lasers with ms, ns, ps and fs pulse duration

Niroj Maharjan^{ab}, Wei Zhou^{a*}, Yu Zhou^b, Yingchun Guan^c, Naïen Wu^d

^aSchool of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

^bAdvanced Remanufacturing and Technology Centre, 3 CleanTech Loop, Singapore 637143

^cSchool of Mechanical Engineering and Automation, Beihang University, 37 Xueyuan Road, Beijing 100191, P. R. China

^dPrecision Laser Solutions Pte. Ltd, 280 Woodlands Industrial Park E5, Singapore 757322

Abstract

Laser surface hardening, used to achieve hardened surface without affecting bulk properties of steels, generally employs continuous-wave laser to do the job. The purpose of this paper is to systematically investigate the use of different pulsed lasers for surface hardening of 50CrMo4 steel. A continuous-wave laser and various pulsed lasers with pulse duration ranging from fs to ms were used for the experiment. It was found that millisecond laser utilizing about 9 times lower power is as effective as continuous-wave laser for surface hardening. It produced an average surface hardness of ~719 HV (2.7 times higher than base material hardness) and ~200 μm hardened depth, which is comparable with continuous-wave laser hardening. Similarly, nanosecond laser could induce both surface hardening effect and material removal depending on the parameters used. However, a shallow hardened depth (of mere ~80 μm) was achieved compared to continuous-wave laser. Furthermore, femtosecond and picosecond lasers did not produce any observable surface hardening effect; instead they resulted in direct surface ablation.

Keywords: laser hardening; pulsed laser; continuous-wave laser; hardness; steel.

* wzhou@cantab.net; phone +65 6790 4700

1. Introduction

Many engineering components such as bearings, shafts, cams and gears are subjected to high stresses during operation. They require hard surfaces to resist wear but should maintain tough inner cores to absorb energy without fracture. Such heterogeneous properties in steel can be engineered by selectively hardening the surface using lasers [1]. Lasers provide localized surface heating which results in austenitization of the heated surface. As the beam moves away, the surface cools rapidly and transforms to martensite with hardness higher than the bulk material.

Generally, continuous-wave (cw) lasers are employed for surface transformation hardening. Selvan et al. [2] used a high power CO₂ laser for localized hardening of AISI 5135 steel and achieved 3-fold increase in hardness and 2-fold increase in wear resistance of hardened surfaces. Kennedy et al. [3] presented an excellent review on use of high power diode lasers in surface hardening and predicted increase in use of such lasers in hardening applications due to their high efficiency, compact size and decreasing capital costs. Shin et al. [4] employed a high power cw Nd:YAG laser to investigate hardening characteristics of S45C carbon steel. They achieved three times higher hardness and wider hardened area than defocused beam using uniform beam profile of Nd:YAG laser. A cw high power diode laser was also utilized by Guarino et al. [5] to improve fatigue life of AISI 1040 carbon steel. Similarly, cw Yb-fiber lasers have been used in hardening of low carbon steels [6,7] and medium carbon bearing steel [8].

The power in these cw lasers ranges from a few watts to kilowatts range. The higher energy input with cw lasers provides an adequate heating effect for phase transformation hardening. On the contrary, pulsed lasers produce an extremely high instantaneous intensity at short pulses which causes phenomenon such as multiphoton absorption and optical breakdown [9]. Thus, they are thought to be unsuitable for surface hardening application, whereby a phase transformation effect is desired rather than material removal.

While cw lasers still dominate this field, some surface hardening studies using pulsed lasers have been reported. Habedank et al. [10] performed both experimental and simulation studies on pulsed laser hardening and discovered that hardening with ms pulsed laser with low-pulse frequencies produced higher hardening depths and higher endurance limits compared to that by cw laser. Yilbas and co-workers [11] performed numerical simulations to study the effect of consecutive laser pulse heating on phase transformation and reported that the laser pulse

parameter alters the sizes of the melting and mushy zones in the surface region. Similarly, Mahmoudi et al. [12] studied the effect of peak and average laser powers on surface hardening of AISI 420 stainless steel with a ms pulsed (0.2-20 ms) Nd:YAG laser. They argue that the laser peak power is a more important parameter than the average power.

Moreover, Nath et al. [13] utilized repetitive laser pulses for surface hardening of AISI 1055 steel. They recorded lower average heating rate and longer soaking time above austenitization temperature than those in cw laser hardening process. These effects were attributed to increase in hardened depth and homogenization of austenite. Jiang et al. [14] recognized the laser pulse energy as the most important parameter for spot hardening of AISI 01 tool steel. They found that short laser pulse durations below 8 ms tend to produce shallower hardening zones. Similar results were obtained by Yasavol et al. [15] who reported that increase of the laser energy and reduction of the laser scanning rate results in deeper melt pool formation. Recently, Tricarico et al. [16] employed a numerical-experimental approach to determine the processing window for surface hardening and melting of hypereutectoid steel using pulsed laser.

From above discussions, it is clear that pulsed lasers carry potential to be used for surface hardening. During pulsed laser irradiation, the total heat input is less compared to the cw laser which should generate less surface distortions and additionally, reduce the adverse effects of excessive surface heating. This can be beneficial in treating intricate parts with complex geometries. Although laser beam shaping of cw laser beam has been shown viable for surface hardening of complex parts [17], pulsed lasers provide higher flexibility than cw lasers due to additional controlling parameters like pulse duration and frequency. In addition, use of pulsed lasers omits the need for expensive optical systems required for beam shaping and eliminates any energy loss associated with it.

However, despite the advantages, a systematic examination on the effect of different pulsed lasers on hardening morphology is still lacking. Therefore, the current research was carried out to systematically investigate the effect of different lasers on surface hardening of steel. Lasers operating at different time scales ranging from ultrashort duration to continuous mode are utilized to perform a panoramic investigation on the prospect of surface hardening of steel. The results indicate that ultrashort pulsed laser might not be feasible for surface hardening application as it results in direct ablation of surface due to very high power density. On the other hand, long pulsed laser shows beneficial effect of using pulses for surface hardening producing comparable hardening effect as with cw laser.

2. Material and methods

The material studied was 50CrMo4 steel with nominal chemical composition as shown in Table 1. It is a low alloy steel with medium carbon content used in bearing applications and often subjected to heat treatment to improve its surface mechanical properties. Representative specimens were extracted from as-received cylindrical bar. Surfaces of these specimens were uniformly ground with progressively finer SiC papers starting from P180 grit up to P2000 grit. This produced an average surface roughness of about 0.8 μm ensuring a similar level of surface absorptivity for all specimens. No absorption coating was used. The polished surface was cleaned with alcohol before performing laser treatment.

Table 1

Chemical composition (in wt%) of 50CrMo4 steel used.

Elements	C	Cr	Mn	Mo	Si	P	S	Fe
wt%	0.51	0.95	0.88	0.20	0.23	0.04	0.04	Bal.

Four types of pulsed lasers – femtosecond (fs), picosecond (ps), nanosecond (ns) and millisecond (ms) lasers, were used to irradiate the specimen. Considering the continuous wave as an extreme case of pulse duration, experiments were also performed using a cw fiber laser (wavelength 1070 nm) to compare the results. The experimental conditions used are reported in Table 2. All experiments were performed in air with a Gaussian energy distribution of laser beam. Experiments were repeated at least twice to establish the repeatability of the process.

It is noteworthy to point out that different laser pulses interact differently with material and produce a range of effects ranging from direct ablation to heating to no effect at all. Some might expect to use similar experimental conditions for all lasers. However, it is not possible to use same parameters for all lasers due to technical limitations (for example, laser sources with ms duration cannot have the repetition rate of a ps laser source).

On the other hand, operating all lasers at similar power density by changing experimental parameters seems to be a reasonable option as it would make the comparison easy. However, it poses two major challenges – (a) the difference in how laser power density is calculated for cw laser and pulsed laser; and (b) the practical implication of having same power density.

Power density can be simply defined as the ratio of power supplied to the area of the laser beam i.e.

$$\text{Power density} = \frac{P}{A}, \quad (1)$$

where P is the power and A is the area of the laser beam. In case of cw laser, P is the total power of the laser beam. For pulsed laser, P represents peak power of the pulse [18], given as

$$\text{Peak power} = \frac{\text{pulse energy}}{\text{pulse duration}}. \quad (2)$$

Based on Eq. (1) and Eq. (2), the peak power (and thus, power density) of ultrashort pulsed lasers are generally higher than that of long pulsed and cw lasers. Mathematically, it is still possible to have same power density for all lasers, but it would not be feasible in practical application. For example, the beam diameter for femtosecond laser needs to be in the range of meters for it to have similar power density as ms laser. Therefore, the only viable option to perform the study was to use different experimental conditions for different laser system.

Table 2

Experimental parameters used for different lasers.

Parameters	fs laser	ps laser	ns laser	ms laser	cw laser
Wavelength (nm)	790	1064	1060	1070	1070
Pulse duration	130 fs	600 ps	220 ns	10 ms	NA
Repetition rate (Hz)	1000	200000	500000	10	NA
Spot diameter (μm)	30	50	120	500	500
Power (W)	1.5	13.5	90	27	250
Scan rate (mm/s)	100	50	200	2	10

The study compares the hardening effect of lasers across a spectrum of laser pulse durations. In order to appreciate the complexity of laser-material interaction, only the results obtained from typical parameters used for different lasers are reported here.

Microstructural features were studied using Carl Zeiss AxioCAM optical microscope, Carl Zeiss Smartproof5 confocal microscope and JEOL 5600LV scanning electron microscope (SEM). The

SEM was equipped with an energy dispersive spectrometry (EDS) system to obtain information on the chemical composition. Surface hardness measurements were made using a Vickers hardness indenter with 100 gf and 15 s dwell time. For cross-section hardness measurements, Agilent G200 nanoindenter was used instead of Vickers indenter owing to the small hardening depth. It used a Berkovich tip and continuously measured the load and the penetration inside the specimen during the entire test. A surface approach velocity of 10 nm/s and a constant depth limit of 600 nm was used for all tests. Series of indents were made using the nano-indenter and average values were taken for reporting.

3. Results and discussion

3.1. As-received 50CrMo4 alloy steel

The microstructure of as-received 50CrMo4 steel before laser irradiation is shown in Fig. 1. The microstructure consisted of pearlite and ferrite produced from annealing process. Under high magnification, spherical and elongated cementite particles were found randomly distributed in the ferrite matrix. The average microhardness of the structure was measured to be 253 ± 20 HV (including both cementite and ferrite).

Fig. 1. Typical microstructure of as-received 50CrMo4 steel, showing carbides at higher magnification (in inset).

3.2. After ultrashort pulsed (fs and ps) laser treatment

Ultrashort laser pulses are characterized by incredibly high peak intensities and interact with materials on a timescale faster than the heat diffusion in the material [19]. The precise nature of ultrashort pulse laser and material interaction results in improved dimensional accuracy and tighter tolerances, reduced collateral damage, and elimination of post-processing steps [20].

Even though ultrashort pulsed lasers are very precise, they might deposit a measurable amount of heat to a substrate when the average laser power is high [21,22]. The thermal energy deposited can result in hardening of surface, but not many investigations are performed in this direction. Hirayama and Obara [23] studied the heat effects of metals such as gold, silver, copper and iron treated with fs laser pulses and found the amorphous metal formation near the surface. They attributed such change to rapid melting and quenching. Similarly, Tamaki et al. [24] demonstrated welding of transparent materials using fs laser pulses, which verifies the thermal effect produced by ultrashort pulses. Moreover, Dumitru et al. [25] found evidence of crystalline structure change in the immediate vicinity of fs laser induced microholes, with the extent of modified zones increasing with increase in fluence. They reported an increase in hardness near the microholes with hardness as high as 11.6 GPa for AISI 52100 steel and 20.5 GPa for AISI M3 steel. It was therefore envisaged that ultrashort laser pulses with high energy can bring changes such as phase transformation and hardening on the remaining surface. Experiments were, therefore, carried out to investigate hardening during fs and ps laser irradiation.

Fig. 2(a) shows the laser treated surfaces after fs laser processing. The surface hardness measurement revealed no change in hardness value. The high peak power of fs pulses resulted in direct ablation of the material. The color of the surface appeared grey. Table 2 shows the chemical composition of the surface obtained from EDS analysis. It shows presence of oxygen (about 8 wt%) on fs laser treated surface which formed due to reaction with air. It is to be noted that weight percentage of carbon measured by EDS might not be accurate as the characteristic X-rays produced by carbon atoms are interfered by inherent noise in EDS signal. Therefore, the carbon weight percent values are not reported in the table.

Similarly, high magnification SEM imaging revealed the presence of laser induced ripples of periodicity 590-630 nm on the irradiated surface (see Fig. 2(b)). The ripples formed due to interaction of surface plasmons with laser beam [26]. The oxide scales formed due to oxidation

could also be clearly observed. Therefore, the obtained morphology was attributed to the combined effect of surface oxidation and formation of surface ripples which act as diffraction gratings [27].

Table 3

Typical elemental surface composition obtained from EDS after irradiation with different pulsed lasers.

Element	Weight percentage (%)		
	fs laser	ps laser	ns laser
C*	-	-	-
O	7.9	3.7	4.0
Cr	1.1	1.3	1.4
Mn	0.5	0.7	0.9
Si	0.2	0.2	0.2
Fe	86.7	91.0	90.0

*values not reported as EDS cannot give accurate carbon weight percent.

Fig. 2. (a) Typical surface after fs laser treatment. The processed area is 20 × 20 mm²; and (b) High magnification image showing laser induced ripples and oxides on the ablated surface.

Similar phenomenon occurred with ps laser pulses. Fig. 3(a) shows a typical surface after ps laser irradiation. As expected, the surface had series of ablation lines corresponding to line scans used for processing. The lines had depth of about 0.5-1 μm . Mild surface oxidation was present as evidenced by presence of oxygen (about 4 wt%) as shown in Table 2. Interestingly, no surface ripples were observed unlike in fs laser treated surface. Moreover, the hardness values also did not show much difference as shown in Fig. 3(b).

Picosecond laser pulses have pulse duration higher than electron cooling time and lower than lattice heating time [28]. Thus, the pulses hitting the metal surface results in instantaneous thermal heating, evaporation and emission of the material [29]. As a result, shallow grooves were created on the surface. However, area of thermal influence of the pulse with such small time of action was insufficient for appreciable energy deposition and transition of the microstructure to martensite. Therefore, no change in hardness was observed.

Fig. 3. (a) Surface after ps laser irradiation showing grooves; and (b) Indents made on transverse section of ps laser treated specimen showing no change in hardness.

3.3. After ns laser treatment

The energy absorbed during ns laser irradiation penetrate to a depth given by thermal diffusion length of the solid with electrons and lattice in thermal equilibrium. This contrasts with fs and ps laser interaction where the penetration depth is given by the diffusion length of hot excited electrons which are not in thermal equilibrium with the lattice during interaction [28]. Depending

on the parameters used, ns laser can achieve material removal as well as surface heating. The material removal capability of ns laser has found widespread application in industries for surface cleaning [30]. However, the residual heating and subsequent hardening is often considered as a side effect of material removal. Buling et al. [31] recently reported surface hardness as high as 900 HV after laser treatment using a pulsed solid-state laser with 1064 nm wavelength, 30 kHz repetition rate and 80 ns pulse duration. While their main objective was to improve the adhesive properties of the bearing steel surface, their result exhibits the potential of using ns laser for hardening.

Laser surface treatment was performed to investigate surface hardening effect using ns laser pulses. Fig. 4 shows a typical surface morphology after ns laser irradiation. The laser scan lines overlap could be clearly observed as the edge of laser spot created stuck out fins of about 2 μm higher height than the surface. These fins were about 60 μm apart and corresponded well with the 50% overlapping used for laser scanning. Oxygen was detected using EDS at the surface as shown in Table 2 which indicates occurrence of surface oxidation during ns laser processing.

Fig. 4. Typical surface after ns laser treatment (90 W power, 220 ns pulse duration, 500 kHz repetition rate) – (a) 3-D profile; (b) 2-D profile and line scan.

Further investigations were carried out to study the cross-section microstructure of ns laser treated samples. Fig. 5(a) shows a cross-section microstructure after ns laser irradiation with 90

W laser power. The laser affected zone is roughly 80 μm thick. The microstructure was analyzed under high magnification SEM. The microstructure near the surface was basically martensitic (Fig. 5(b)). A few small spherical carbides were present in the near surface region which were undissolved carbides during fast heating with pulsed laser. Apparently, such microstructure resulted from the austenitization of the surface layer followed rapid quenching due to heat dissipation into the bulk. Furthermore, the heating effect from successive laser pulses produced tempered martensite with needle-like structure in the overlap zone (Fig. 5(c)). The sub-surface region just beneath the laser hardened zone was exposed to heating from the laser pulses which is enough for tempering; but not for austenitization. As a result, tempered microstructure with lots of carbides existed in this heat affected zone (Fig. 5(d)). The base microstructure remained unaffected by the heating from laser and consisted of ferritic microstructure with elongated and spherical carbides.

Fig. 5. Microstructure after ns laser treatment – (a) Cross section microstructure; (b) martensite in laser hardened zone; (c) tempered martensite in overlap zone; and (d) tempered structure in heat affected zone showing undissolved carbides.

Hardness measurements were made on the cross-section to confirm the obtained microstructure. Fig. 6 displays a series of indents made on the cross-section using nano-indenter. As can be observed, the hardness in the laser hardened region is very high compared to base material hardness. It gradually reduced in heat affected zone and finally reaches base material hardness at depth of about 80 μm . An intermediate hardness (of about 500 HV) was recorded in the overlap zone which was attributed to tempering due to successive laser passes. The results are summarized in Table 4, which shows that the obtained hardness co-related well with the microstructure.

Fig. 6. Indents made on transverse section of ns laser treated specimen showing variation in hardness along the depth. The specimen was etched with 2% nital after indentation test to reveal the microstructure.

Table 4

Average hardness values at different zones of the laser treated specimen after ns laser treatment.

Region	Hardness (HV)
Laser hardened zone	642 ± 45
Overlap zone	500 ± 49
Heat affected zone	473 ± 21
Base region	253 ± 20

The obtained results, thus demonstrate the potential of surface hardening using ns laser. With the selected setting of 11% duty cycle (220 ns pulse width and 2000 ns cycle), peak temperature at the surface reached austenitization temperature, but did not exceed melting point. Therefore, the area experienced local quenching and a hardened surface was formed. However, the fast outflow of energy exceeded energy accumulation and limited its thermal diffusion depth. As a result, a shallow depth of hardening (of about 80 μm) was achieved which is not enough for real industrial application.

3.4. After ms laser treatment

Fig. 7(a) shows a typical surface after ms laser treatment. Surface melt ripples were observed on the irradiated surface which indicate the partial melting and re-solidification of the surface. Thus, laser surface hardening process included both phase transformation hardening and surface melting. A number of globular bumps were randomly dispersed on the surface. These bumps had somewhat circular shape and varied from 5-50 μm in size. EDS analysis, as shown in Table 5, revealed that they were composed of Fe-Cr-Mn-Si-O and identified as the metal slag that appear on the surface during heating. Oxides were also present on the surface due to reaction of the metal with air.

Table 5

Elemental composition at the surface after ms laser treatment.

Elements	Weight percentage (%)	
	Normal surface	Bump
C*	-	-
O	11.9	37.6
Cr	1.4	4.2
Mn	1.6	23.2
Si	0.6	16.4
Fe	81.8	14.8

*values not reported as EDS cannot give accurate carbon weight percent.

The melt ripples are formed by the combined effect of surface-tension gradients in the molten pool and free surface oscillation near solidification front (Fig. 7(b)) [32]. When a ms laser irradiates a metal surface, the surface tension at the position where the laser irradiates is lower compared to the cooler edges which has higher surface tension. Marangoni flow arises due to

such gradient of surface tension along the interface between two fluids. The radially outward Marangoni flow pushes the molten metal towards the edges creating depression at the center [33]. As the laser moves away, the molten metal rapidly solidifies producing a ripple like effect. Moreover, the heating also results in segregation of alloying elements at the surface which forms metal slag at the surface [34].

Fig. 7. (a) Millisecond laser treated surface with overlapping beam spots (27 W power, 10 ms pulse duration, 10 Hz repetition rate). (b) Schematic diagram showing melt ripple formation.

Fig. 8 shows a typical cross section microstructure of ms laser treated surface. The microstructure is similar to as obtained in ns laser treatment and could be clearly distinguished into laser hardened zone (Fig. 8(b)), heat affected zone (Fig. 8(c)) and base microstructure. The laser hardened zone had martensitic structure while heat affected zone consisted of tempered microstructure.

Fig. 8. (a) Cross section micrograph after ms laser treatment; (b) Martensite in laser hardened zone; and (c) Tempered microstructure in heat affected zone.

The obtained microstructure and hardness are affected by laser parameters like power, scanning speed, repetition rate, processing environment and pulse width [8]. Fig. 9 shows a typical hardness profile for sample hardened with 27 W average laser power. Hardness in excess of 700 HV was obtained near the surface. Depending on the power density used, the depth of hardening ranged from 100 μm to 1000 μm . The improved hardness was attributed to rapid austenitization and subsequent cooling of the area affected by laser pulse which forms hard martensite phase. For the typical microstructure shown in Fig. 9, the hardness remained at about 700 HV up to a depth of about 80 μm after which it reduced to an intermediate hardness of 450 HV. The intermediate hardness region extended to a depth of about 200 μm . Finally, it reduced to base material hardness at about 200 μm . The results indicate that a significant hardening effect can be achieved with ms laser due to effective heat transfer.

Millisecond laser pulse deposits large amount of energy onto the steel surface in a short time. The energy must be conducted quickly into the bulk of material for martensitic phase

transformation. At the sub-surface region, the effect of laser beam heating is not as influential as near the surface. Therefore, it is heated to a lower temperature than the surface which on cooling forms partially hardened microstructure (Fig. 8(c)) with intermediate hardness.

Fig. 9. Graph showing variation of hardness along the depth after ms laser treatment.

3.5. After cw laser treatment

Continuous-wave laser is generally employed for surface hardening as it can achieve superior surface hardness and large hardening depth. A typical surface morphology after hardening using a cw laser is shown in Fig. 10(a). Unlike in ms laser treatment, the surface ripples were not observed; instead a large melt pool formed due to higher heat input which resolidified forming a continuous laser hardened line with lumps of Fe-Cr-Mn-Si-O on the surface. The cross-section microstructure revealed a C-shaped laser hardened zone formed due to the continuous exposure of the surface to the laser.

The microstructure was similar as in ms laser treatment (Fig. 10(b)). Fig. 11 shows the microhardness measurement along the depth. The peak hardness was about 777 HV which is similar as that obtained during ms laser treatment. The hardness remained constant in the

hardened region until it suddenly dropped to parent microstructure hardness. Contrary to ms laser treatment, no intermediate zone with medium hardness was observed. This suggested the tempered zone was either very small or almost absent during continuous mode of beam operation. Nevertheless, it is noteworthy to point out that a much higher laser power (250 W) is required in continuous mode for the similar depth of hardened zone as in ms laser (27 W).

Fig. 10. (a) Typical surface after hardening using cw laser (250 W power, 10 mm/s scanning speed); (b) Cross-section microstructure of the hardened zone.

Fig. 11. Variation of hardness along the depth for typical cw laser irradiated sample.

3.6 Discussion

The lasers used in this study operate at different time scales and different power densities. The major results and the effects on the surface after laser irradiation with different lasers are illustrated in Table 6 and Fig. 12. No significant change in hardness was observed for fs and ps pulsed lasers. Instead, they resulted in surface ablation (Fig. 12(a)) which could be employed for precision machining and removing surface contaminants in manufacturing and remanufacturing industries [35]. Nanosecond lasers supplied higher heat input than ultrashort pulses and were capable of inducing both material removal and surface hardening effect (Fig. 12(b)). Therefore, ns lasers are ideal for surface cleaning as well as other surface modifications such as marking [36] and polishing [37].

Millisecond laser produced a hardened surface with a tempered zone with intermediate hardness (Fig. 12(c)). The cw laser beam hardening resulted in similar hardening effect as with ms laser. The only difference was the absence of a distinct tempered zone (Fig. 12(d)). The continuous delivery of laser energy into the surface by cw laser beam resulted in almost uniform hardness in the region where the austenitization temperature was reached. Although some tempering might have occurred at the boundary between laser hardened zone and base material, absence of a distinct tempered zone suggests the heat dissipating into bulk of the material was insufficient to temper a large area in sub-surface region. On the contrary, the cyclic heating and cooling by ms laser promotes long range carbon diffusion producing distinct tempered zone.

Interestingly, even with lower power of ms laser, the hardness and depth were comparable to that of cw laser. This is possibly because heating rate is higher in case of cw laser than that in pulsed laser [13]. This leads to higher A_{c3} and homogenization temperature in cw laser hardening than in pulsed laser, which necessitates the use of high power. On the other hand, in case of ms laser, the surface remains at high temperature for a very short time. This limits austenite grain growth producing fine grained martensite with high surface hardness [38]. The results suggest that ms laser can be used to replace expensive high power cw laser for surface hardening of components.

Table 6

Comparison of hardening effect of different laser systems.

	Average hardness (HV) in		Depth of laser treated zone (μm)	Remarks
	Laser hardened region	Base material		
fs and ps laser	261	258	-	No hardening effect
ns laser	642	253	~80	Insufficient hardened depth for practical application
ms laser	719	270	~200	Tempered zone in sub-surface region
cw laser	733	265	~200	Absence of distinct tempered zone

Fig. 12. Schematics of laser processing using – (a) fs and ps laser showing surface ablation and no hardening effect; (b) ns laser with surface material removal and hardening of surrounding area; (c) ms laser showing laser hardened zone and tempered zone; and (d) cw laser showing hardening of laser affected area.

4. Conclusions

The comparative investigation of laser surface hardening using pulsed lasers with ms, ns, ps and fs pulse duration and cw laser was performed in this work. The major findings from the study are presented below:

- As expected, fs and ps lasers resulted in direct ablation and removal of material from the steel surface. Therefore, they were considered unsuitable for improving surface hardness of steel.
- Nanosecond laser induced surface hardening effect and hardness as high as 642 HV was achieved without any melting. However, the hardened depth was too shallow (about 80 μm) due to insufficient heat accumulation which might be beneficial for surface modifications such as cleaning and marking.
- An effective hardening was achieved after ms laser irradiation with hardness reaching above 700 HV in the laser hardened zone. The depth of hardened zone was about 200 μm for a typical treatment chosen and can vary from 100 – 1000 μm depending on the laser parameters used.
- It was also found that the ms laser could generate surface hardness and hardening depth of same magnitude as cw laser using about 9 times lower power than cw laser.

The study shows the possibility of using low cost ms lasers for effective surface modification and improving micro-hardness which can appear economically more feasible in comparison to using expensive high-power lasers used nowadays for these purposes.

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References

- [1] A.K. Nath, S. Sarkar, Laser Transformation Hardening of Steel, in: Adv. Laser Mater. Process., Elsevier, 2018: pp. 257–298.

- [2] J.S. Selvan, K. Subramanian, A.K. Nath, Effect of laser surface hardening on En18 (AISI 5135) steel, *J. Mater. Process. Technol.* 91 (1999) 29–36.
- [3] E. Kennedy, G. Byrne, D.N. Collins, A review of the use of high power diode lasers in surface hardening, *J. Mater. Process. Technol.* 155–156 (2004) 1855–1860.
- [4] H.J. Shin, Y.T. Yoo, D.G. Ahn, K. Im, Laser surface hardening of S45C medium carbon steel using ND:YAG laser with a continuous wave, *J. Mater. Process. Technol.* 187–188 (2007) 467–470. doi:10.1016/j.jmatprotec.2006.11.188.
- [5] S. Guarino, M. Barletta, A. Afilal, High Power Diode Laser (HPDL) surface hardening of low carbon steel: Fatigue life improvement analysis, *J. Manuf. Process.* 28 (2017) 266–271.
- [6] S. Sarkar, M. Gopinath, S.S. Chakraborty, B. Syed, A.K. Nath, Analysis of temperature and surface hardening of low carbon thin steel sheets using Yb-fiber laser, *Surf. Coatings Technol.* 302 (2016) 344–358.
- [7] M.H. Farshidianfar, A. Khajepouhor, A. Gerlich, Real-time monitoring and prediction of martensite formation and hardening depth during laser heat treatment, *Surf. Coatings Technol.* 315 (2017) 326–334.
- [8] N. Maharjan, W. Zhou, Y. Zhou, N. Wu, Influence of operating parameters on morphology of laser hardened surfaces, in: *High-Power Laser Mater. Process. Appl. Diagnostics, Syst. VII*, International Society for Optics and Photonics, 2018.
- [9] M.S. Brown, C.B. Arnold, Fundamentals of laser-material interaction and application to multiscale surface modification, *Laser Precis. Microfabr.* 135 (2010) 91–120.
- [10] G. Habedank, J. Woitschig, T. Seefeld, W. Jüptner, F. Vollertsen, R. Baierl, H. Bomas, P. Mayr, R. Schröder, F. Jablonski, Endurance limit of pulsed laser hardened component-like specimens—experiment and simulation, *Mater. Sci. Eng. A.* 488 (2008) 358–371.
- [11] S.Z. Shuja, B.S. Yilbas, S.M.A. Khan, Laser consecutive pulse heating and phase change: influence of spatial distribution of laser pulse intensity on melting, *Int. J. Therm. Sci.* 48 (2009) 1960–1966.
- [12] B. Mahmoudi, M.J. Torkamany, A.R.S.R. Aghdam, J. Sabbaghzade, Laser surface

- hardening of AISI 420 stainless steel treated by pulsed Nd:YAG laser, *Mater. Des.* 31 (2010) 2553–2560.
- [13] A.K. Nath, A. Gupta, F. Benny, Theoretical and experimental study on laser surface hardening by repetitive laser pulses, *Surf. Coatings Technol.* 206 (2012) 2602–2615.
- [14] J. Jiang, L. Xue, S. Wang, Discrete laser spot transformation hardening of AISI O1 tool steel using pulsed Nd: YAG laser, *Surf. Coatings Technol.* 205 (2011) 5156–5164.
- [15] N. Yasavol, A. Abdollah-Zadeh, M. Ganjali, S.A. Alidokht, Microstructure and mechanical behavior of pulsed laser surface melted AISI D2 cold work tool steel, *Appl. Surf. Sci.* 265 (2013) 653–662.
- [16] L. Tricarico, A. Ancona, G. Palumbo, D. Sorgente, R. Spina, P.M. Lugarà, Discrete spot laser hardening and remelting with a high-brilliance source for surface structuring of a hypereutectoid steel, *Mater. Des.* 115 (2017) 194–202.
doi:10.1016/j.matdes.2016.10.079.
- [17] P. Sancho, M.A. Montealegre, J. Dominguez, P. Alvarez, J. Isaza, Dynamic control of laser beam shape for heat treatment, *J. Laser Appl.* 30 (2018) 32507.
- [18] E. Assuncao, S. Williams, Comparison of continuous wave and pulsed wave laser welding effects, *Opt. Lasers Eng.* 51 (2013) 674–680.
- [19] P.T. Mannion, J. Magee, E. Coyne, G.M. O’connor, T.J. Glynn, The effect of damage accumulation behaviour on ablation thresholds and damage morphology in ultrafast laser micro-machining of common metals in air, *Appl. Surf. Sci.* 233 (2004) 275–287.
- [20] X. Liu, D. Du, G. Mourou, Laser ablation and micromachining with ultrashort laser pulses, *IEEE J. Quantum Electron.* 33 (1997) 1706–1716.
- [21] D. V Tran, Y.C. Lam, B.S. Wong, H.Y. Zheng, D.E. Hardt, Quantification of thermal energy deposited in silicon by multiple femtosecond laser pulses., *Opt. Express.* 14 (2006) 9261–9268. doi:10.1364/OE.14.009261.
- [22] R. Fang, A. Vorobyev, C. Guo, Direct visualization of the complete evolution of femtosecond laser-induced surface structural dynamics of metals, *Light Sci. Appl.* 6 (2017) e16256.

- [23] Y. Hirayama, M. Obara, Heat effects of metals ablated with femtosecond laser pulses, *Appl. Surf. Sci.* 197 (2002) 741–745.
- [24] T. Tamaki, W. Watanabe, J. Nishii, K. Itoh, Welding of transparent materials using femtosecond laser pulses, *Jpn. J. Appl. Phys.* 44 (2005) L687.
- [25] G. Dumitru, V. Romano, H.P. Weber, H. Haefke, Y. Gerbig, E. Pflüger, Laser microstructuring of steel surfaces for tribological applications, *Appl. Phys. A Mater. Sci. Process.* 70 (2000) 485–487.
- [26] J. Bonse, S. Höhm, S. V Kirner, A. Rosenfeld, J. Krüger, Laser-induced periodic surface structures—a scientific evergreen, *IEEE J. Sel. Top. Quantum Electron.* 23 (2017) 1–15.
- [27] Y.C. Guan, W. Zhou, Z.L. Li, H.Y. Zheng, Femtosecond laser-induced iridescent effect on AZ31B magnesium alloy surface, *J. Phys. D: Appl. Phys.* 46 (2013) 425305.
- [28] B.N. Chichkov, C. Momma, S. Nolte, F. Von Alvensleben, A. Tünnermann, Femtosecond, picosecond and nanosecond laser ablation of solids, *Appl. Phys. A.* 63 (1996) 109–115.
- [29] J. Stasic, M. Trtica, B. Gakovic, S. Petrovic, D. Batani, T. Desai, P. Panjan, Surface modifications of AISI 1045 steel created by high intensity 1064 and 532 nm picosecond Nd: YAG laser pulses, *Appl. Surf. Sci.* 255 (2009) 4474–4478.
- [30] Y.C. Guan, G.K.L. Ng, H.Y. Zheng, M.H. Hong, X. Hong, Z. Zhang, Laser surface cleaning of carbonaceous deposits on diesel engine piston, *Appl. Surf. Sci.* 270 (2013) 526–530.
- [31] A. Buling, H. Sändker, J. Stollenwerk, U. Krupp, A. Hamann-Steinmeier, Laser surface pretreatment of 100Cr6 bearing steel—Hardening effects and white etching zones, *Appl. Surf. Sci.* 378 (2016) 564–571.
- [32] T.R. Anthony, H.E. Cline, Surface rippling induced by surface-tension gradients during laser surface melting and alloying, *J. Appl. Phys.* 48 (1977) 3888–3894.
- [33] Y. Guan, W. Zhou, H. Zheng, M. Hong, Y. Zhu, B. Qi, Effect of pulse duration on heat transfer and solidification development in laser-melt magnesium alloy, *Appl. Phys. A Mater. Sci. Process.* 119 (2015) 437–442.

- [34] H.J. Grabke, V. Leroy, H. Viefhaus, Segregation on the surface of steels in heat treatment and oxidation, *ISIJ Int.* 35 (1995) 95–113.
- [35] N. Maharjan, W. Zhou, Y. Zhou, Y. Guan, Ablation morphology and ablation threshold of Ti-6Al-4V alloy during femtosecond laser processing, *Appl. Phys. A.* 124 (2018) 519.
- [36] S.T. Hendow, S.A. Shakir, Structuring materials with nanosecond laser pulses, *Opt. Express.* 18 (2010) 10188–10199.
- [37] C.P. Ma, Y.C. Guan, W. Zhou, Laser polishing of additive manufactured Ti alloys, *Opt. Lasers Eng.* 93 (2017) 171–177.
- [38] T. Miokovic, V. Schulze, D. Lohe, O. Vohringer, Influence of heating rate, cooling rate and numbers of pulses on the microstructure of AISI 4140 after short-time-hardening, *Int. J. Mater. Prod. Technol.* 24 (2005) 207–223.

Graphical abstract

Highlights

- Millisecond laser of 9 times lower power is as effective as cw laser in surface hardening and produces hardness as high as 719 HV.
- Nanosecond laser is less effective than cw laser in surface hardening. It produces shallow hardened depth ($\sim 80\text{ }\mu\text{m}$) with hardness of about 642 HV.
- Femtosecond and picosecond lasers result in no hardening of surface.