**Investigation on Effect of Laser Pulsing Parameters on Surface Hardening of Bearing Steel**

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**Abstract:** Bearing steel in hardened and tempered condition is widely used in rotating devices, machines and automobiles. The universal popularity of this steel for these applications transpire from the various attractive technological advantages like high hardenability, high hardness, high strength and good formability coupled with low cost. However, many-a-times, excessive wear along with noise/vibration causes premature failure and/or necessitate early replacement. Furthermore, contact fatigue and bulk toughness are often found to be inadequate at times in heavy duty/load applications and/or thin-section bearings. Engineering the surface of prior-hardened bearing steel by laser surface hardening to further enhance surface hardness to a limited depth without affecting the bulk can be gainfully utilized for tailoring tribological properties to improve life. In the present work, the effect of pulsed-wave (PW) hardening parameters on surface hardening of 1.0%-C steel with prior through-hardened condition is investigated and case depth, hardness and microstructure analysis are discussed in detail. Results indicated enhanced microstructural refinement with partially dissolved carbide globules in PW-processed case as compared to that processed under CW mode. 25-30% higher peak hardness could be achieved in PW-processed case with minimal reduction in core hardness as compared to that of CW-processed counterpart. On the whole, the PW mode of processing showed vast improvement in hardness with significant reduction in distortion and post-process machining requirement**.**

***Keywords*:** Laser surface hardening, Continuous-wave, Pulsed-wave, Bearing Steel.

1. **Introduction**

Bearing steel is a material often used in components for precision measuring tools, dies, rotating devices, machines and automobiles [1]. It requires high hardness, wear resistance and toughness [2], since they are used in poor working environment. The high abrasion and wear enhances friction which leads to premature failure and as a result required improvement in surface properties of the component. Conventional hardening processes such as high-frequency induction hardening, flame hardening and carbonizing technologies are widely used in industrial practices. However, for surface hardening of high-precision parts, if the process is not controlled properly it may tend to overheat or melt the part. Moreover uncontrolled heat-input imparts deleterious effects such as large heat affected zone, surface deformation and inhomogeneous hardness distribution. In 1970’s, the advent of high-power laser development has led the way for using lasers to become an important tool for improving surface hardness by transformation hardening mechanism. As compared to conventional surface hardening techniques, laser treated surface produces higher hardness with refined structure coupled with high stress and meagre strain and thereby greatly improving surface properties at reduced costs and provide tremendous economic benefits. The laser transformation hardening (LTH) process, a directed energy beam assisted surface engineering technique, is fast and can achieve hardening in the work piece with minimal deformation [3-5]. LTH is highly controllable with high cooling rate possible upon self quenching without affecting the bulk material [6,7]. The hardening effect is due to the changes of austenite-martensite transformation [8-10].

High power diode lasers of the order of 6KW can be effectively used for surface hardening of steels provided the working parameters are optimized to get the required properties of the treated layers on the materials and/or components [11,12]. In this work an attempt has been made to enhance

surface hardness of the bearing steel by LTH process and correlate the microstructure and surface mechanical properties with processing parameters. Although many reports are available highlighting applicability of conventional continuous-wave (CW) laser hardening processing of steels, the effective control of microstructure by controlling process cooling rate (peak temperature) and distortion are negligible. In CW mode, continuous increase in temperature happens along the treated track although constant power is maintained and a result comparatively high heat accumulation with higher peak temperature is achieved with scanning duration. Whereas, in PW mode of processing, the laser pulses will be modulated, alternatively with ON/OFF sequence, depending on the pulse duration and frequency and thereby control heating cycle and surface temperature of the workpiece. Thus these two modes will result in different cooling rates which will directly affect the microstructural changes in the treated case. The majority of published researchers utilized CW mode of operation. There is no comprehensive study on the PW mode of hardening. It is expected that the pulsing nature of laser effectively controls the process by changing the number of heating and cooling cycles and the distribution of the laser power density in the workpiece. In the present work, the effect of pulsed-wave (PW) hardening parameters on surface hardening of bearing steel with prior through-hardened condition is investigated. Influence of the processing conditions on case depth, hardness and microstructure are discussed in detail.

1. **Experimental Procedures**

The material used in the present work is a 1.0%-C Steel with spheroidized and hardened with microstructure comprising of globular carbides in martensite matrix and retained austenite [13]. The flat steel coupons of 3-mm thick were subjected to laser surface treatment (irradiation) by employing CW and PW modes using high power diode laser (Laserline GmbH, Germany) integrated to 6-axis robotic workstation (Reis Robotics GmbH, Germany). The multi-mode 915-980 nm diode laser beam (Gaussian mode in fast axis and top-hat mode in slow axis) transferred through 1000-µm fiber optic cable was tailored into a rectangular spot of 20 mm x 5 mm (Full Width Half Maximum) by employing appropriate collimating homogenizing and focusing optics. Laser surface hardening (LSH) treatment has been carried out at fixed working distance of 300 mm to have uniform laser intensity distribution throughout the experimentation.

In order to analyze the hardened layer depth and sub-surface microstructure of the treated surfaces, metallographic samples were sectioned from the cross section of the treated tracks using a EDM wire cutting machine and the samples were mounted and ground as per standard metallographic sample preparation methods and etched using 2% Nital reagent for microstructural analysis using Opto-digital Microscope (Olympus Corporation, Japan) and a Scanning Electron Microscopy (SEM) (Hitachi Model S-4300SE/N, Japan) equipped with Energy Dispersive X-ray Spectrometer (EDS) unit. Few laser treated layers were also subjected X-ray diffraction analysis to analyze phases present in the microstructure of the treated layers. In order to examine the influence of the laser treatment on the micro-hardness of the steel substrates, Vickers microhardness tester (Walter UHL, VMHT 104) was employed at 500 g load with a spacing of 150 µm between indentations.

1. **Results and discussions**
   1. **Case depth and microstructure analysis**

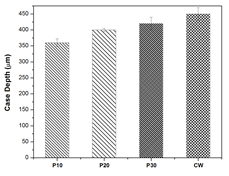
Initially, preliminary experiments under PW mode by varying pulse width at a fixed applied energy density of 32 J/mm2 were conducted to assess its effect on case depth and surface hardness of the treated layers. Fig. 1 illustrates effect of pulse width during PW mode of processing and CW mode of processing conditions on case depth of the hardened layers. With increase in pulse width (during PW mode of processing) case depth was found to increase as a direct consequence of the enhanced heat input (average power). The case depth in P10, P20 and P30 layers were observed to be 360 ± 12 µm, 400 ± 5 µm and 420 ± 20 µm respectively. However, case depth of the treated layer processed under CW mode (with similar average power to that of PW processed samples) was found to be highest to the tune of 450 ± 20 µm. Indeed thermal diffusion period during austenetization enhances due to CW mode of processing and as a result marginal enhancement in case depth could be observed as compared to that of P30 layer. Surface hardness measurements on PW processed samples showed decrease in their values with increase in pulse width. It was found to reduce from 1000HV in P10 layer to 920HV in P30 layer and could be attributed to increase in critical cooling rate during the laser processed thermal cycle. Indeed thermal diffusion period during austenetization gets reduced with pulse width and as a result reduction in case depth could be envisaged with enhancement in surface hardness. It is clear that high cooling rate associated with PW mode of laser treatment cycle profoundly influence the extent of martensitic transformation in the microstructure. In order to study comparative effect of cooling rate associated with mode of processing, P10 sample processed with similar average power to that CW mode were compared and analysed subsequently for hardness distribution and microstructural changes.

Fig.2 Effect of pulsing parameters on case depth of treated layers

Fig.1 Effect of pulsing parameters on case depth of treated layers

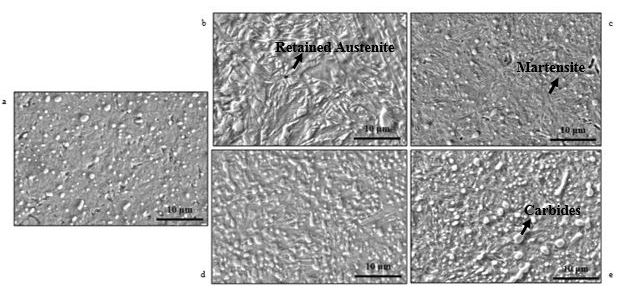
To gain further understanding on the influence of contrasting thermal cycles associated with mode of processing, XRD, SEM and EDS analysis of the microstructures were carried out. Although not presented here, XRD analysis of the treated surfaces indicated higher broadening of α-Fe (martensite) peaks in PW layer than in CW layer. Additionally, retained austenite content was observed to be lower in PW processed layer than in CW layer. Fig.2 illustrates high magnification SEM micrographs within various regions (HZ and Core zones) of interest of laser treated layers processed under PW and CW modes. The size and morphologies of globular precipitates (observed to be complex carbides of Fe and Cr from EDS analysis), previously observed in untreated core microstructure, was found to get modified with mode of processing on account of vast variation in laser treatment cycle condition and its associated cooling rate effects. The microstructure of untreated substrate (depicted in Fig 2(a)) shows predominantly presence of martensite (tempered) matrix with pockets of retained austenite and globular carbides of Fe and Cr. The microstructural refining effect (martensite matrix) was found to be greater in HZ region of PW layer than that observed in HZ region of CW processed layer. Similar effects of microstructural coarsening with variation in heat input conditions are reported in the study conducted by R. Akhtar and co-workers and attributed to peak temperature variation [14]. Apparently density of carbide globules and retained austenite were found to be higher in hardened microstructure of CW layer than that observed in PW layer. This is expected as thermal cycle of PW mode of processing experiences low period of austenetization (low peak temperature) and higher cooling rate during laser treatment cycle. Conversely, CW mode of processing experiences relatively lower cooling rate (although higher than that of conventional heat treatment cycle) with increased duration in austenetization, thereby facilitating higher carbon diffusion into the prior austenite grains and carbide globules. Thus coarsening of microstructure with enlargement of prior-austenite grains and carbide globules could be observed in hardened region microstructure of CW layer as evident from Fig 2(a). However, comparing microstructures of core regions below the transition zones of PW and CW layers showed vide variation on account of wide variation in thermal cycle the prior-hardened steel experiences. The tempering (softening) effect on martensite matrix with dissolution of prior carbides is clearly evident in the core region of CW processed layer as evident from its microstructure (Fig. 2(c)) This could be attributed to higher heating temperature (thermal diffusion) the region experiences associated with higher peak temperature of laser treatment cycle. Thus weakening of martensite matrix with dissolution of carbides and austenite could be anticipated in the microstructure of core region of CW processed layer than PW one. Similar effects of softening associated with laser treatment cycle were reported in the study conducted by Donato and co-workers and attributed to thermal diffusion effects [15].

Fig. 2 Cross-sectional SEM micrographs of various zones within the laser-hardened layers of bearing steel processed under different modes: (a) Untreated Substrate; (b) HZ zone processed under CW mode; (c) Core zone processed under CW mode; (d) HZ zone processed under PW mode; (e) Core zone processed under PW mode

* 1. **Hardness distribution in treated layers**

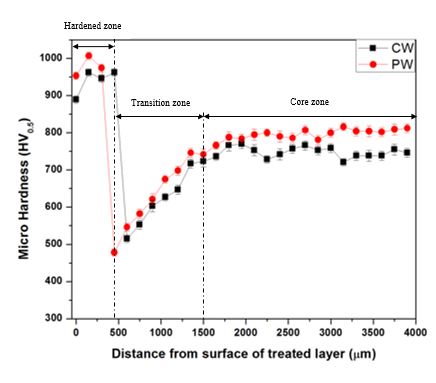
Fig. 3 illustrates cross-sectional microhardness distribution profiles obtained across the depth of laser treated layers processed under different operating modes (CW & PW). The hardness distribution in various zones of interest (HZ, TZ and CZ) are marked for easy illustration and understanding. The HZ region of PW mode exhibited higher improvement in hardness (1000 + 20 HV) than that in CW mode (940 + 10HV), in convergence with refinement in martensite matrix and refined globular carbides observed in its microstructure. Indeed rapid quenching in PW mode of processing leads to the precipitation of fine carbides inside the martensite plates along with pinning of dislocation facilitate enhancement in hardness. Thus amount, morphology and finesses of martensite and retained austenite phases in the microstructure determine the hardness obtained in the treated layer. At the interface region of HZ/TZ region, there is substantial dip in hardness (as low as 450 + 20 HV) which could be attributed to heating temperature experienced (thermal diffusion) in the region leading to over tempering of martensite and coarsening of carbides. Hardness distribution in the HZ region of CW mode is less (940 + 10HV) compared to PW mode, due the difference in cooling rates and thus affecting the hardness values of both surface and core. Comparing hardness in CZ of layers processed with PW and CW modes, it is clear that, hardness reduced to significantly low (730 + 20 HV) in CW layer, well below that of untreated substrate. This could be attributed to higher tempered martensitic transformation observed in the microstructure as previously reported. Thus PW mode of processing facilitates in less tempering effect in the core region and thereby facilitating in higher retention of core hardness.

Fig. 3 Hardness distribution along the cross-section of the Laser Hardened steel

**Conclusions**

From the present study conducted on laser surface hardening of bearing steel, following conclusions can be drawn:

1. Hardness as high as 1000-1020 HV could be achieved in PW-processed case with minimal reduction in core hardness as compared to that of CW-processed counterpart whose hardness achieved was 920-950 HV along with significant reduction in core hardness.
2. PW mode of processing facilitates in enhancing microstructural refinement with partially dissolved carbide globules with reduced case depth as compared to that processed under CW mode.
3. On the whole, the PW mode of processing indicated vast improvement in hardness and thereby possible improvement in life of bearing with significant retention of bulk hardness and reduced distortion and thereby reducing post-process machining requirements.

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