Discrete laser spot transformation hardening of AISI O1 tool steel using pulsed Nd:YAG laser

Jiang, Jiaren; Xue, Lijue; Wang, Shaodong

Publisher's version / Version de l'éditeur:
https://doi.org/10.1016/j.surfcoat.2011.05.016
Surface & Coatings Technology, 205, 21-22, pp. 5156-5164, 2011-05-23

Discrete Laser Spot Transformation Hardening of AISI O1 Tool Steel Using Pulsed Nd:YAG Laser

Jiaren Jiang[1], Lijue Xue, Shaodong Wang
National Research Council of Canada, Industrial Materials Institute, 800 Collip Circle, London, ON, N6G 4X8, Canada

Abstract

Discrete laser spot transformation hardening is a process that creates isolated laser hardening spots, usually distributed in a certain pattern, on a component surface, covering only a fraction of the surface region that is being treated. The process offers several unique advantages for tribological applications, including improved lubrication conditions and wear performance and increased productivity. However, very limited information is available on the appropriate selection of processing parameters to achieve optimal results. In this paper, discrete laser spot hardening of AISI O1 tool steel has been studied using a pulsed Nd:YAG laser. Effect of various laser processing parameters, including laser pulse energy, pulse duration and defocus distance, on characteristics of the laser treated spots are investigated. Maps are experimentally established for processing parameter selections in discrete laser spot transformation hardening of the AISI O1 tool steel. Results show that the maximum diameter and depth of transformation hardening zones with no surface melting increase with the increase of laser pulse energy. However, they are not markedly affected by laser pulse duration. On the other hand, longer pulse durations at a given pulse energy reduce the size of softening zone surrounding the central hardening zone and are thus more favourable for most practical applications. Short laser pulse durations below 8 ms tend to produce shallower hardening zones and are not recommended for wear applications.

Keywords
Laser hardening, transformation hardening, laser texturing, AISI O1 tool steel

1. Introduction

Laser transformation hardening refers to the process where high power lasers are used to produce hard surface layers in ferrous materials via solid-state martensitic phase transformation. Reviews on this process presented by Donaldson (1986) and Ion (2002) have provided extensive coverage on fundamental understandings of the process, state-of-the-art technical progress up to the respective publication dates, material properties after the treatment, and industrial practices and applications. The solid-state transformation involved in this process has the advantages of enhancing component performance without or with little modifications to the finished component surface and causing little dimensional changes/distortions. Therefore, it can be used as the final step in finishing precision mechanical components and moulds/dies. This process was perhaps one of the first laser based fabrication methods to be commercially applied, which saw

---

[1] Corresponding author.
Present address: National Research Council of Canada, Institute for Fuel Cell Innovation, 4250 Wesbrook Mall, Vancouver, BC, V6T 1W5, Canada.
Email: jiaren.jiang@nrc-cnrc.gc.ca; tel: 1-604-221-3107; fax: 1-604-221-3001

the successful industrial implementation on surface hardening of gear housing in the automotive industry by GM back in 1974 (Ion, 2002).

Many investigations have shown that laser transformation hardening is very effective in increasing surface hardness and improving wear resistance of ferrous materials, such as 0.45C% steel (Munteanu et al., 1997), En18 steel (Selvan et al., 1999), and ductile cast iron (Ju et al., 1988; Papaphilippou et al., 1996). Sridhar et al. (2007) used a high power diode laser to harden AISI 1018, AISI 4140, and gray cast iron that improved dry sliding wear resistance by a factor of 10-12 as compared with the (normalisation treated) base metals. Hwang et al. (2002) experimentally established process parameters for laser surface hardening of piston rings used for marine diesel engines and obtained almost twice the wear life of the untreated ones. Asnafi et al. (2004) applied laser surface hardening in small and medium-sized production trimming dies and demonstrated significantly improved service life as compared with induction- and through-hardening treatment.

Currently, the most commonly used method of laser transformation hardening uses a shaped laser beam to continuously scan across the surface of a component to produce a full surface coverage of hardening layer in a specified region. However, studies by Iino and Shimoda (1987) showed that surface treatment of normalised carbon steel, JIS S50C, by a continuous CO_2 laser considerably reduces hardness in the overlap zones due to tempering effect, which is usually undesirable for wear applications.

One of the plausible solutions for resolving the above problem is discrete laser spot hardening (or laser dot matrix hardening) that creates isolated/discrete hardening spots arranged in certain patterns on the component surface. This concept was first introduced by Schulze and Keitel (1988) who used electron beams for the hardening of a steel surface. The concept was also applied to the treatment of mill cylinders for improving formability, surface morphology, and deep drawing properties of metal sheets (Renaud et al., 1989). In this application, controlled surface roughness is created on the roller surface with plateaus and valleys, which are transferred to the rolled metal sheet surfaces. The textured features formed on the rolled metal sheets trap lubricant and collect detrimental wear debris during the metal forming process, resulting in the elimination of galling and much reduced tooling wear. Pantelis et al. (1997) used a pulsed CO_2 laser to produce hard spots arranged in regular patterns on gray cast iron surface. Dry sliding wear resistance (against a steel pin) was improved by 25% as compared with flame hardening. Papaphilippou and Jeandin (1996) investigated laser spot hardening of nodular cast iron using a CO_2 laser operated in the pulsed mode. Dry sliding wear resistance (against an alumina ball) was increased by three times as compared with the untreated iron matrix (with a pearlitic substrate). No significant effect on wear resistance of the treated surface was observed by either the pattern of hard spot arrangements or the surface coverage of hard spots in the range of 10 to 100%.

Xue et al. (1999) used a pulsed Nd:YAG laser to create a uniform distribution of transformation-hardened spots on AISI O1, D2 and 4340 steel surfaces covering various percentages of the desired surface region. Thrust washer wear testing on the discrete laser spot ("dot matrix") hardening treated AISI O1 steel showed doubled wear resistance as compared with the tempered substrate (HRC 40-42) and was equivalent to that of the AISI O1 steel fully hardened to a hardness of HRC 60. Surface coverage in the range of 20-100% had little effect on its wear resistance.

It is apparent that the discrete laser spot treatment by forming isolated/discrete hardening spots on a component surface offers several unique advantages for improving wear performance of materials over the conventional laser surface hardening with complete surface coverage:

- Prevention of hardness reduction of previously formed laser hardening zones by subsequent laser irradiation
- Reduction/elimination of stresses and distortions
- Creation of advantageous lubrication conditions by forming lubricant reservoirs
- Considerably increased productivity for surface hardening treatment because only a small fraction of the surface needs to be treated to achieve the same levels of wear performance

As compared with CO_2 lasers, Nd:YAG lasers have a shorter wavelength and thus normally do not need to coat the surface that is to be treated. Such lasers are more easily controllable and can be delivered to component surfaces by fibre optics and are therefore more suited for laser transformation hardening than the CO_2 lasers. However, very limited data is available on the appropriate selection of processing parameters to achieve optimal results (Xue et al., 1999). In this paper, discrete laser spot hardening of AISI O1 tool steel has been studied using a pulsed Nd:YAG laser. Effect of various laser processing parameters, including laser pulse energy, pulse duration and defocus distance, on characteristics of the laser treated spots are investigated. Maps are experimentally established for processing parameter selection in discrete laser spot transformation hardening of the AISI O1 tool steel. Guidelines for the use of the maps are discussed.

2. Experimental method

2.1 Material

AISI O1 tool steel plate with an initial thickness of 9.55 mm was used in this study. The nominal compositions of the steel are (wt%): C 0.90, Mn 1.20, V 0.20, W 0.50, Cr 0.50, and Fe balance. The steel was heat treated to HRC 46 ± 1 using the following conditions: 788 °C x 30 min + oil quench + tempering at 427 °C x 2 hr + furnace cool to 258 °C followed by air-cooling. At least 0.25 mm of material was ground off from the plate surfaces to remove oxidation and decarburization layers. Two substrate surface finishes were investigated: Ra 0.31 μm (through grinding) and Ra 0.01 μm (polishing with 3 μm diamond paste). The former represents a regular engineering surface finishing and the latter is typical final finishing in mould/die making.

2.2 Laser treatment

A Lasag 500W Nd:YAG laser was used for the laser treatment test. The laser was operated in a pulsed mode and was delivered with a 600 μm diameter glass fibre. During the treatment, the laser beam was kept stationary, while the sample was manipulated to move in relation to the beam by a CNC motion system. The following parameters were systematically changed: pulse energy (10 to 25 J/pulse), pulse duration (4 to 20 ms), and positive defocus distance (+5.1 to +17.8 mm, depending on pulse energy and pulse duration). The treatment was conducted in ambient air. All the results refer to single pulse laser treatment.

2.3 Measurement of dimensions of surface hardening and melting zones

As will be illustrated below, various zones are formed on the laser treated surface, i.e., melting zone, transformation hardening zone, and softening zone. Each of the zones has unique appearance and/or colour and can be identified under optical microscope. Compared with hardness measurement, this method is much easier and was thus used to measure the diameters of transformation hardening zone and melting zone.

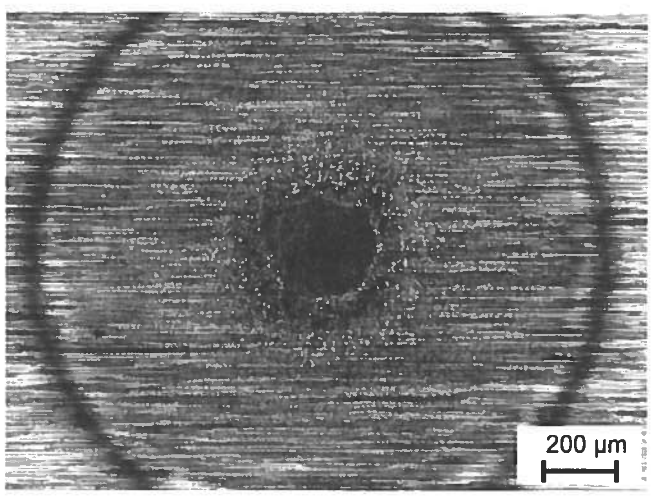
The depths of laser treated spot were measured on cross-sections of specially treated samples under a given range of processing conditions. In preparing the cross-sectioning samples, narrow strips of steel substrate were used. The substrate strip was fixed on the CNC machine table with one (long) edge being accurately aligned with the X-direction motion. Then a series of laser treatment spots using pre-determined processing parameters was produced on the steel substrate along the X motion direction. The sample was then sectioned by precision grinding to remove half of the laser treated spots (about 25 μm above the centre line), which were then embedded in epoxy and polished for microscopic observation and depth measurement.

3. Results and discussion

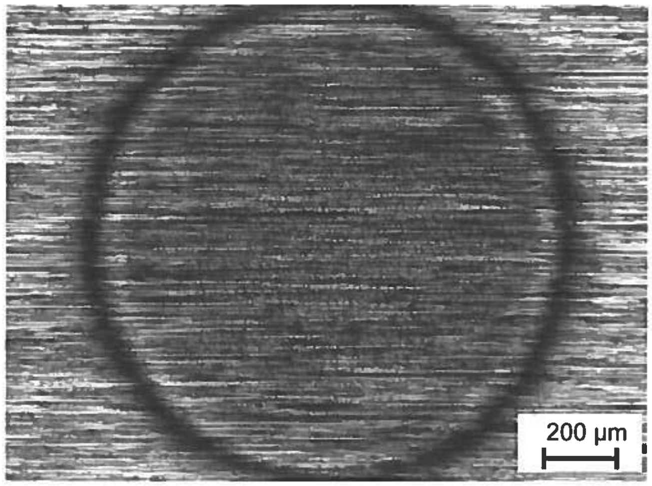
3.1 Characteristics of laser treated spots

Fig. 1 shows some typical optical images of laser treated spots obtained at different energy density levels at the substrate surface. The appearance of a laser treated spot varies according to the applied laser energy density. Higher energy density is achieved by higher pulse energy and/or shorter pulse duration and/or lower defocus distance. When the substrate was irradiated with high energy densities, melting occurs in the spot centre (Fig. 1a). Surrounding the melting zone is an area whose colour gradually changes from blue (near the centre) to brown to orange and to white (original metal surface colour). The ring on the outmost of the laser treated area has a black/dark blue colour. As the energy density decreases (e.g., increasing defocus distance at a given pulse energy and pulse duration), the melting zone decreases and eventually disappears (Fig. 1b). At further lower energy densities, only the black/dark blue ring or simply a black/dark blue spot is obtained (Fig. 1c). When the energy density is further decreased to below certain level, no marking could be observed on the substrate surface.

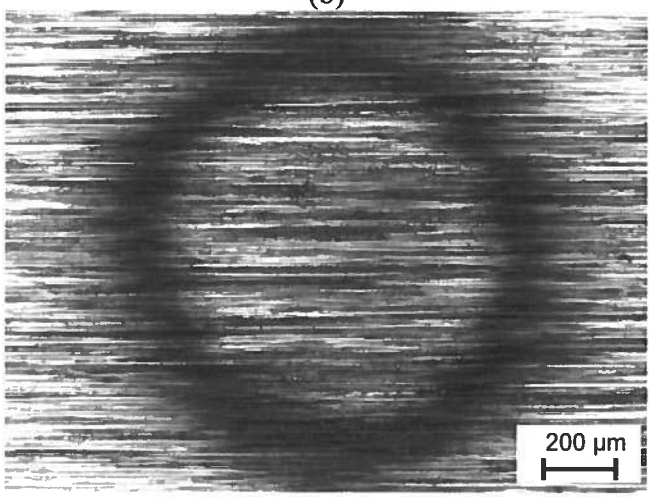
Similar characteristics of laser treated spots were observed on polished substrate surfaces.



(a)



(b)



(c)

Figure 1 Typical optical microscopic images of laser treated spots on the ground AISI O1 steel surface at different energy density levels. The laser processing parameters were as follows: pulse energy 25 J/pulse, pulse duration 20 ms and defocus distances of (a) +11.4 mm, (b) +12.4 mm, and (c) +14.0 mm.

Fig. 2 shows a montage of microstructure on the cross-section of a laser spot treated sample. The laser hardening and melting zones were essentially not attacked by the chemical etching; these showed a white layer under microscope. Secondary carbides precipitated from the hyper-eutectoid AISI O1 tool steel substrate in the melting zone are considerably coarser than those formed in the transformation hardening zone, as is shown in Fig. 3.

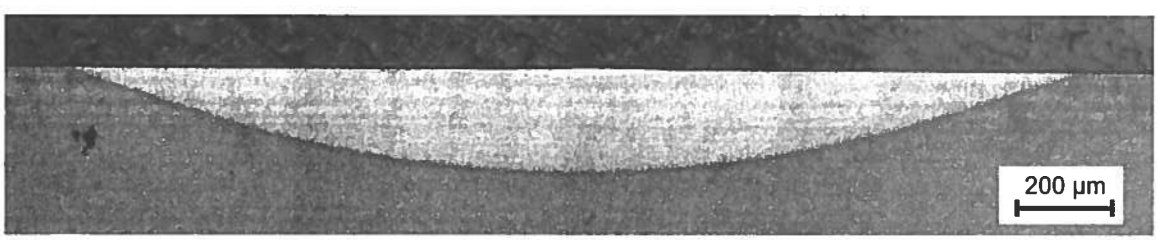


Figure 2 Cross-section view of microstructure of a laser treated sample (25 J/pulse, 20 ms pulse duration, defocus +11.4 mm).

(a) (b)

Figure 3 SEM microstructures within the laser treated layer in (a) melting zone and (b) transformation hardening zone.

3.2 Hardness distribution across the laser treated area

Fig. 4 shows the variation of micro-hardness (HV_{300}) measured across the diameter of a laser treated surface area. The substrate surface finish before laser treatment was Ra 0.01 μm. In general, the laser treatment considerably increased the hardness of the pre-heat treated AISI O1 tool steel. However, a region of hardness decrease is observed surrounding the hardening zone, which is identifiable under microscope as between the white and the outer black/dark blue rings. The mechanism for the formation of this softening zone can be explained as due to further tempering of the tempered martensite substrate.

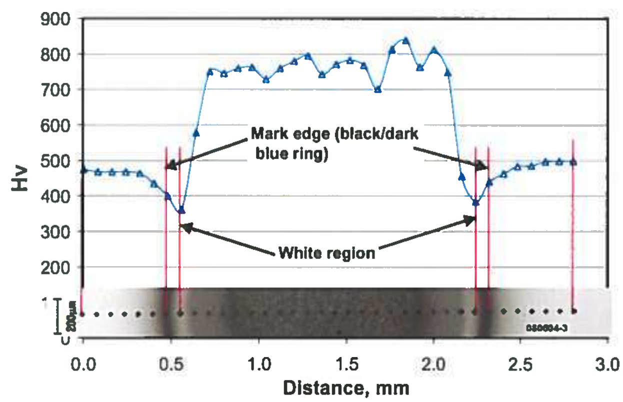


Figure 4 Hardness distribution across the diameter of a laser treated spot (polished substrate surface, laser treatment parameters: 25 J/pulse, 20 ms pulse duration, defocus +12.4 mm).

The existence of a softening zone after laser treatment is confirmed by plotting the variation of hardness of laser treated spot as a function of defocus distance (laser pulse energy 25 J/pulse and pulse duration 20 ms), Fig. 5. At short defocus distances, a large portion of the surface within the laser spot is transformation hardened and is much harder than the tempering heat-treated AISI O1 steel substrate. With the increase of defocus distance, the dimensions (diameter and depth) of the transformation-hardening zone decrease due to the decrease of energy density. The measured hardness also decreases. When the defocus distance is further increased above certain value, the surface temperature within the whole laser spot is below the critical austenisation transformation temperature and no martensitic transformation hardening occurs. The laser heating leads to tempering of the substrate. As a result, the surface hardness is lower than that of the heat-treated substrate. At even higher defocus distances, heating effect from the laser irradiation becomes negligible and the surface hardness approaches that of the original heat-treated steel substrate.

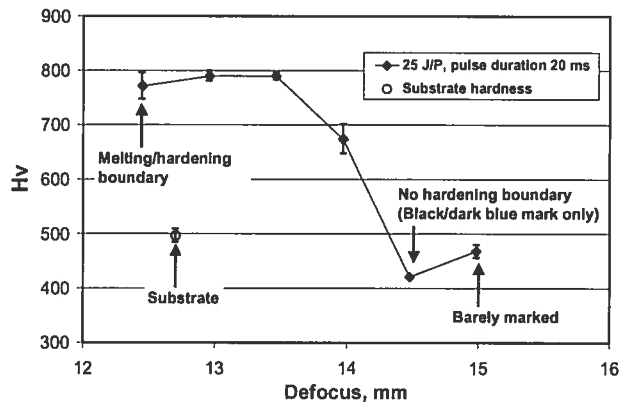


Figure 5 Effect of defocus distance on hardness of laser treated AISI O1 steel.

Measurement on samples with ground substrate surface finishes (Ra 0.31 μm) showed the same hardening effect and hardness distributions cross the laser treated spot, except that the softening zone was not as clearly identifiable due to data scatter caused by rougher surfaces.

Measurements on samples with central melting zones showed that there is no significant difference in hardness between the melting zone and the transformation hardening zone.

Colour change within the laser treated area is a result of surface oxidation and is closely related to surface temperature distributions. Based on this close corresponding relationship between hardness and laser treated steel surface colour (surface temperature), the diameter of hardening zone was reliably measured using a microscope. The melting zone diameter can also be easily measured under microscope.

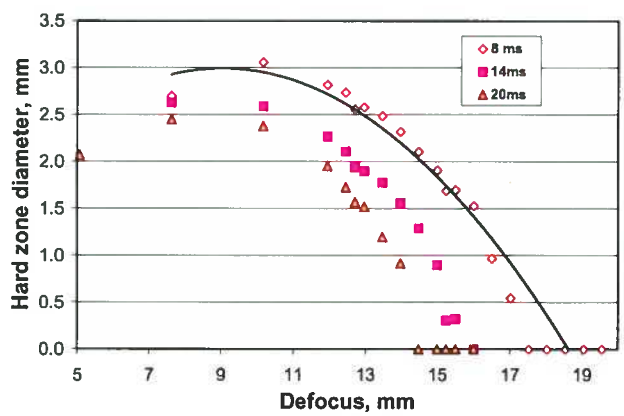
3.3 Parameter maps for laser transformation hardening

A series of testing were carried out to determine the ranges (windows) of laser processing conditions at various pulse energy levels that allow the formation of only transformation hardening without causing surface melting for the AISI O1 tool steel using the pulsed Nd:YAG laser.

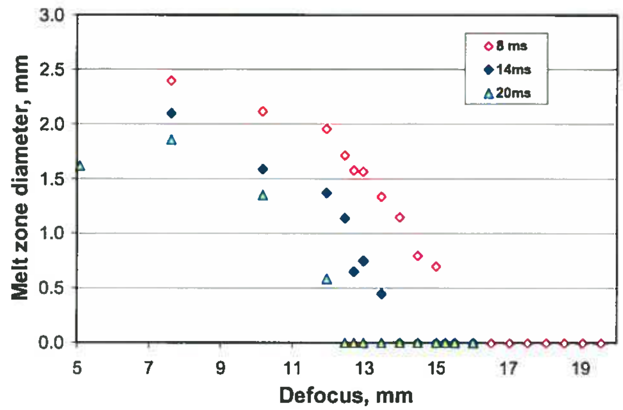
Fig. 6 shows two typical plots for the variation of diameters of hardening zone (Fig. 6a) and melting zone (Fig. 6b) as a function of defocus at various pulse durations at pulse energy of 25 J/pulse. In Fig. 6a, a maximum hardening zone diameter appears at a defocus distance of approximately 9 mm. Within the tested parameter range, similar trend is also observed on the melting zone diameter plot at the pulse duration of 20 ms (Fig. 6b).

The initial increase in hardening zone diameter with the increase of defocus distance at the low defocus distance is presumably caused by two effects. (a) Laser spot size on the sample surface decreases with decrease in defocus distance, with a minimum at the focal point. At low defocus distances, heat input is focused on a small area. Therefore the heat transfer distance and hardening/melting zone is small; this will increase as defocus distance increases. (b) The very high energy density at low defocus distances leads to the melting or even evaporation of sample surface. According to computer simulation results, the steel surface at the centre of the laser spot can reach a temperature that is above the evaporation temperature of steel (3300 °C) at 7.5 mm defocus distance, 25 J/pulse and 8 ms pulse duration. A large portion of the input energy is thus consumed as latent heat for melting and/or evaporation. One might argue that the melting latent heat is released during solidification of the melt. However, there is a time lapse between the austenisation heating up of the substrate surrounding the laser spot centre (non-melting zone), which occurs during the laser irradiation, and the solidification latent heat release, which occurs after the laser pulse. Temperature in the regions surrounding the central melting zone will have considerably reduced as a result of rapid heat transfer into the substrate by the time the solidification latent heat is conducted to these regions. The reheating will lead to a relatively lower overall temperature than that can be reached if the same amount of available energy/heat is input at the same time during the laser irradiation. As a result, less heat is available for transferring into the surrounding area to cause transformation hardening.

On the other hand, the decrease in hardening and melting zone diameter with further increase in defocus distance is relatively easy to understand. With the increase in defocus distance, energy density decreases because the input laser energy is distributed to an increased surface area. When energy density at the peripheral areas of the laser spot is reduced to below certain critical level, the heating temperature of substrate at these regions will fall below the critical temperature for austenisation transformation. As a result, no transformation hardening effect is observed. Therefore, the hardening zone diameter decreases with further increase in defocus distance. Similar argument can be applied to the variation of melting zone diameter as a function of defocus distance.



(a)



(b)

Figure 6 Typical variations of (a) hardening zone diameter and (b) melting zone diameter as a function of laser defocus distance at different pulse durations (pulse energy = 25 J/pulse).

Comparison testing shows that substrate surface finish has little effect on the size and variation of transformation hardening zone and melting zone under the same laser treatment conditions, as is shown by the example in Fig. 7. It is known that energy absorption of Nd:YAG lasers by steel surfaces is enhanced through the rapid initial surface oxidation and decolouration. Thus energy loss due to laser scattering within the studied roughness range (Ra 0.01 to 0.31 μm) seems to be minimal, leading to similar surface heating and hardening effects.

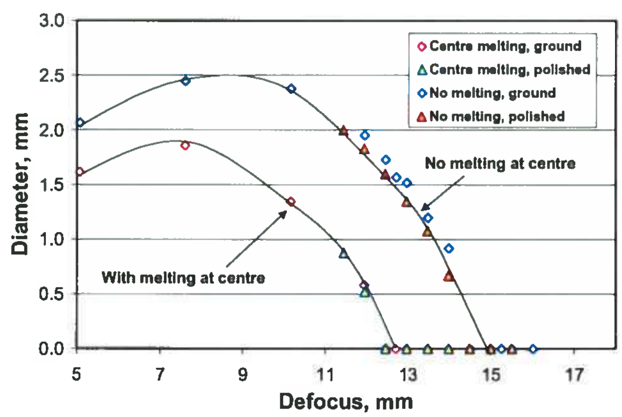
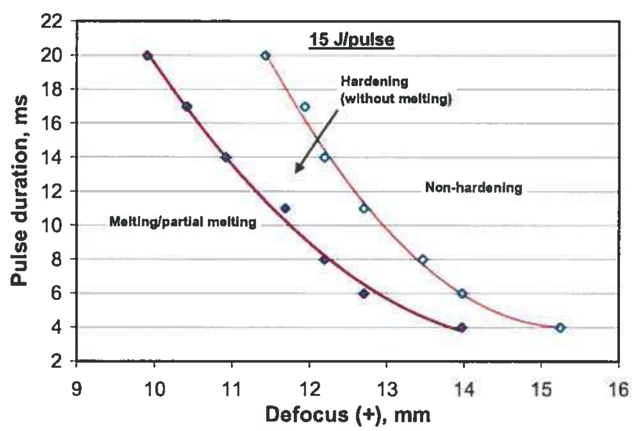


Figure 7 Effects of substrate surface finish on variation of transformation hardening zone and melting zone diameters during pulsed Nd:YAG laser surface treatment.

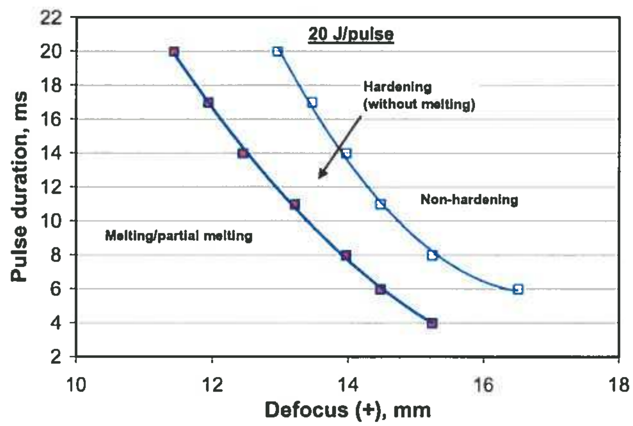
Based on the plots shown in Fig. 6, a range of laser processing conditions can be determined for achieving laser transformation hardening without causing surface melting. As mentioned earlier, both surface melting and transformation hardening leads to similar increased surface hardness (Fig. 4). However, under melting/partial melting conditions, the surface is potentially heavily oxidised, shrinkage porosities may form due to the melting-solidification process, and surface roughness and/or geometry may also be altered. These are obviously undesirable for most applications. On the other hand, at too large defocus distances, the pulsed laser treatment does not cause transformation hardening. Instead, surface softening due to the laser tempering/annealing effect is observed at certain defocus distance (Fig. 5). At given laser pulse energy level and pulse duration, three types of laser treated spot can be produced at different defocus distances: (a) Surface melting occurs at the centre of laser treated spot when the defocus distance is short; (b) at intermediate defocus distances, transformation hardening occurs at the central portion of the laser treated area without melting; and (c) at long defocus distances, no hardening occurs within the whole laser irradiated area where the temperature is below the critical austenisation temperature for this steel. Using data in Fig. 6, maps can be constructed that plot two boundaries separating these three types of laser treated spots that are formed using different laser processing parameters. Thus, the defocus distance at which the melting zone diameter becomes zero on Fig. 6b is the critical defocus distance separating the meltingand hardening regions. At defocus distances greater than this critical value, laser transformation hardening is obtained without causing surface melting at the spot centre. Similarly, from Fig. 6a, a critical defocus distance can be determined where the hardening zone diameter becomes zero. This critical value separates the hardening and non-hardening regions, above which no transformation hardening occurs. By plotting the variation of these critical defocus distances obtained at different laser pulse durations for a given pulse energy, laser transformation hardening processing maps for the AISI O1 steel were experimentally established, as shown in Fig. 8.

Results obtained on polished steel substrate at pulse energy of 25 J/pulse are included in Fig. 8c. It is again shown that substrate surface finish within the investigated range has no apparent effect on the selection of laser treatment parameters, which is consistent with results shown earlier (Fig. 7).

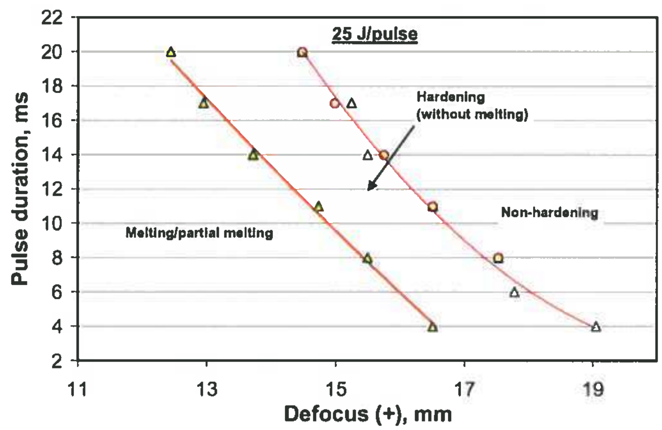
The use of these maps will be discussed later.



(a)



(b)



(c)

Figure 8 Processing parameter maps for discrete laser spot transformation hardening of AISI O1 tool steel at laser pulse energy levels of (a) 15 J/pulse, (b) 20 J/pulse, and (c) 25 J/pulse.

3.4 Effects of laser pulse duration on transformation hardening of the AISI O1 steel

At a given laser pulse energy, the maximum diameter of laser transformation hardening zone without surface melting are achieved under the conditions (defocus distance, laser pulse energy and laser pulse duration) along the boundary separating the melting and hardening regions as established in Fig. 8 (the solid lines). The variations of such maximum diameter of transformation hardening zone as a function of laser pulse duration at various pulse energy levels are shown in Fig. 9. There is generally a slight increase in the maximum achievable diameter of hardening zone with increase in laser pulse duration, although this effect is not so significant for the pulse energy level of 20 J/pulse. To obtain larger hardening zone diameters, higher laser pulse energies are needed.

On the other hand, laser pulse duration does have considerable effect on the softening zone size. As has been shown in Fig. 4, there is a softening zone in a laser treated spot surrounding the central hardening zone. Fig. 10 shows the variation of area ratio of the hardening zone to the overall laser heat affected area (including melting, hardening, and softening zones) as a function of laser pulse duration at the various laser pulse energy levels. The relative softening area decreases (the hardening area ratio increases) with increase in laser pulse duration. From a practical application point of view, in order to achieve the best transformation hardening results with minimum softening effect, longer laser pulse durations are preferable.

The trend shown in Fig. 10 can be explained as follows. Energy density distribution within a laser spot roughly follows a normal distribution with a maximum at the spot centre. For the same laser pulse energy input, when a longer pulse duration is used, the input energy from the spot centre is dissipated more to the outer surrounding regions. The overall effect of this heat transfer is a relatively more uniform energy distribution than at shorter pulse durations, leading to the formation of a larger area within the laser spot that is heated to above the critical austenisation temperature. Meanwhile, the maximum laser heated area is expected to be mainly a function of laser spot size (defocus distance) and will change only slightly with pulse duration (Fig. 9). Thus, the relative area ratio of transformation hardening zone to the overall laser heated zone increases with the increase in laser pulse duration.

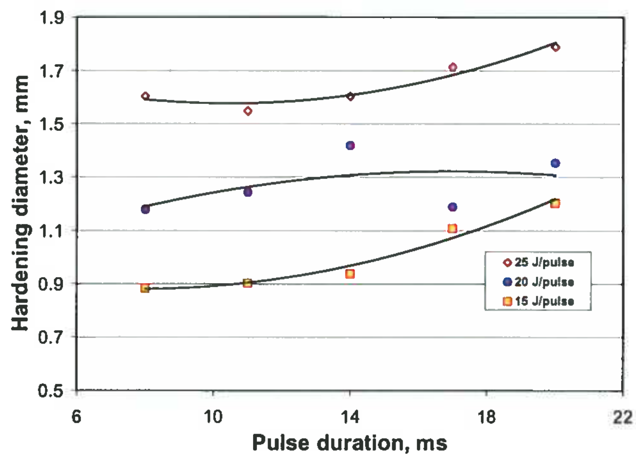


Figure 9 Variation of maximum diameter of hardening zone with no surface melting that is achievable at given pulse energy levels as a function of laser pulse duration.

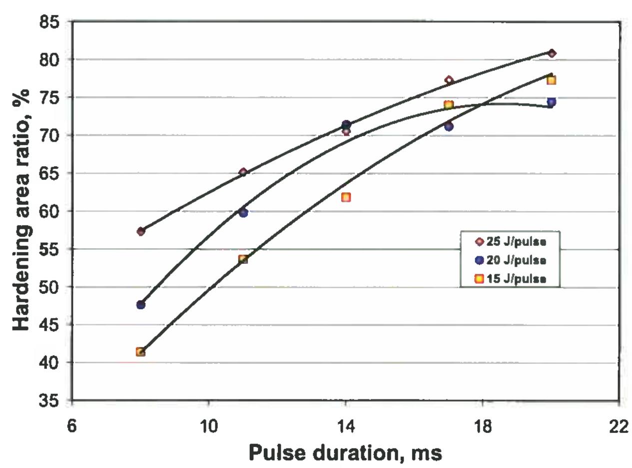


Figure 10 Effect of laser pulse duration on area ratio of hardening zone to overall laser heat affected area at different laser pulse energy levels.

The laser pulse duration does not seem to have significant effect on the hardness of transformation hardening zone, as shown in Fig. 11. These results were measured on samples treated under processing conditions along the melting/hardening boundary given in Fig. 8c for pulse energy of 25 J/pulse. This is comprehensible because the steel substrate will go through very similar austenisation/martensite transformation processes to form similar microstructures when only transformation hardening occurs without surface melting.

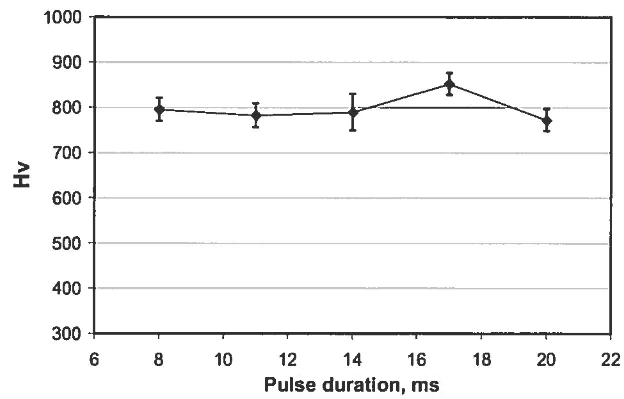
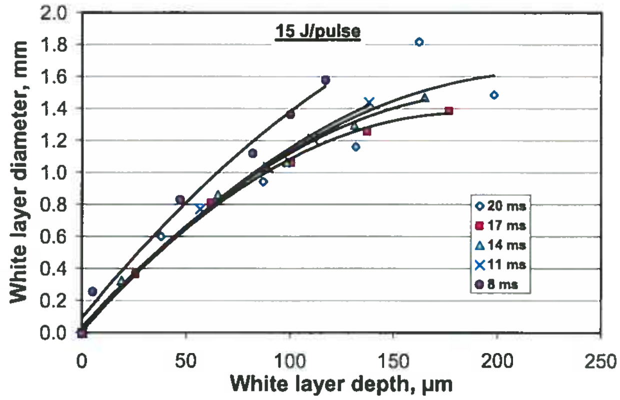


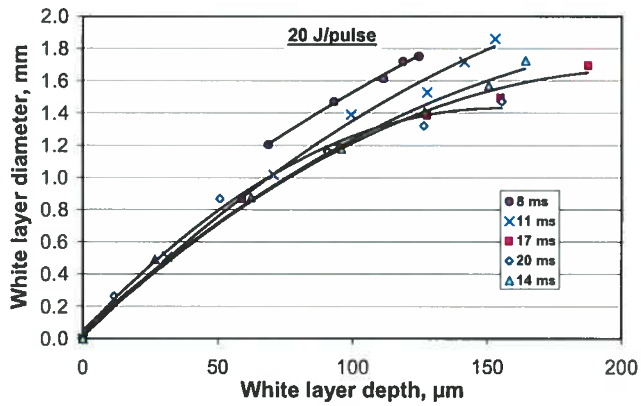
Figure 11 Variation of hardness in the transformation hardening zone as a function of laser pulse duration on samples treated under conditions along the surface melting/hardening boundary as given in Fig. 8c for pulse energy of 25 J/pulse.

3.5 Relationship between diameter and depth of the laser transformation hardening zone

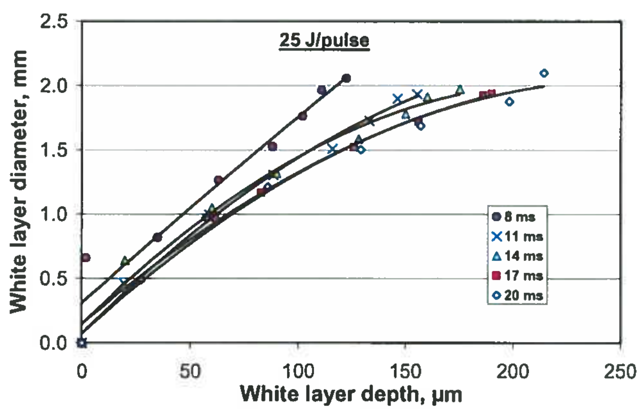
The depth and width (diameter) of white layers on the cross-section of pulsed laser treated samples were measured on a series of specially prepared samples under a given range of processing conditions. The results are shown in Fig. 12. Similar trends are obtained for all the three tested laser pulse energy levels. Data for the short pulse duration of 8 ms clearly separates from that for the rest pulse durations. To produce the same hardening zone diameter, the depth is considerably shallower at pulse duration of 8 ms than that at the other longer durations. For pulse durations greater than 8 ms, data seems to fall within a very narrow range, although data scatter increases at larger diameters/depths where shorter laser pulse durations tend to produce shallower hardening layers than at longer pulse durations. This effect of pulse duration on hardening layer depth can presumably be attributed to the limited thermal conductivity of the steel. Thus, heat loss due to radiation increases at shorter pulse durations (higher surface temperatures) and less heat is transferred to the subsurface region for transformation hardening, producing shallower hardening zones.



(a)



(b)



(c)

Figure 12 Relationship between diameter and depth of white layers formed on AISI O1 steel substrate after single pulse laser treatment at the different pulse energies: (a) 15 J/pulse, (b) 20 J/pulse, and (c) 25 J/pulse.

3.6 General discussion

From a practical application point of view, processing parameters for laser transformation hardening should be selected by considering several factors.

The processing parameter maps in Fig. 8 are useful in selecting discrete laser spot surface treatment conditions for the AISI O1 steel. Similar maps can be constructed for other steels using the same procedures. For most practical applications, laser transformation hardening should be conducted using conditions within the hardening only zone, i.e., with no surface melting. The conditions should generally be selected at close to the boundary separating the surface melting and hardening only regions, although under certain circumstances parameters towards the hardening/non-hardening boundary may be used to obtain smaller diameter hardening spots. Laser treatment using conditions along the hardening/non-hardening boundary will produce discrete softening spots. Such treatment might be potentially useful for certain applications. For example, under lubricated sliding wear conditions where the substrate is already very hard and martensitic transformation may not offer further significant hardness improvement, such soft spots formed on the wear surface may be preferably worn out and act as lubricant reservoirs to significantly improve wear life of the component.

The size/diameter of transformation hardening spots is mainly determined by laser pulse energy. Higher pulse energy levels produce larger transformation hardening spots (Fig. 9). Larger spot sizes are generally favourable for improved productivity if a certain surface hardening area coverage is to be achieved.

Based on results presented earlier, longer laser pulse durations are more preferable. According to Fig. 9, laser pulse duration does not have significant effect on the maximum achievable spot diameter of transformation hardening zone. However, Figs. 10 & 12 indicate that longer pulse durations allow for the formation of uniform transformation hardening spots with minimum softening zone size and larger hardening layer depths.

Finally, laser pulse durations shorter than 8 ms under the current laser setup conditions are not recommended, as short laser pulses tend to produce shallower hardening layers (Fig. 12).

4. Conclusions

Discrete laser spot hardening of tempered AISI O1 tool steel has been studied using a pulsed Nd:YAG laser. Processing parameter maps incorporating laser pulse energy, pulse duration and defocus distance are experimentally established. Results show that laser pulse energy is the main significant factor affecting the dimensions (diameter and depth) of transformation hardening zone. The higher the laser pulse energy, the larger the transformation hardening zone can be achieved without causing surface melting. Laser pulse duration affects the size of softening zone surrounding the central hardening zone in a laser treated spot. The softening zone size decreases with increase in the pulse duration at a given pulse energy. It is suggested that laser pulse durations much greater than 8 ms should be used for achieving higher hardening effects.

Acknowledgement

The authors wish to acknowledge Mr. Nelson Santos and Mr. Brian Gibson for their assistance in conducting the laser treatment experiments.

References

Asnafi, Nader, Johansson, Tuve, Miralles, Marc, Ullman, Andrreas, 2004. Laser surface-hardening of dies for cutting, blanking or trimming of uncoated DP600. In: Recent Advances in Manufacture and Use of Tools & Dies and Stamping of Steel Sheets, October 5-6, 2004, Olofström, Sweden, pp. 193-214.

Donaldson, E.G., 1986. Surface hardening by laser – a review. The British Foundryman, 262-275.

Hwang, Jong-Hyun, Lee, Yun-Sig, Kim, Dae-Young, Youn, Joong-Geum, 2002. Laser surface hardening of gray cast iron used for piston ring. JMEPEG, 11, 294-300.

Iino, Y., Shimoda, K., 1987. Effect of overlap pass tempering on hardness and fatigue behaviour in laser heat treatment of carbon steel. Journal of Materials Science Letters 6, 1193-1194.

Ion, J.C., 2002. Review – Laser transformation hardening. Surface Engineering, 18, 14 – 31.

Ju, C.P., Chen, C.H., Rigsbee, J.M., 1988. Laser surface modification of ductile iron: Part 2 Wear mechanism. Materials Science & Technology, 4, 167–172.

Munteanu, V., Levcovici, D.T., Parischiv, M. M., Levcovici, S. M., 1997. Wear behavior of mosaic shaped surfaces produced by laser hardening. Surface Engineering, 13 (1), 75–78.

Pantelis, D.I., Pantazopoulos, G., Antoniou, S.S., 1997. Wear behavior of anti-galling surface textured gray cast iron using pulsed-C02 laser treatment. Wear 205, 178-185.

Papaphilippou, C. and Jeandin, M., 1996. Spot laser hardening. Journal of Materials Science Letters 15, 1064-1066.

Papaphilippou, C., Vardavoulias, M., Jeandin, M., 1996. Effects of CO_2 laser surface hardening in the unlubricated wear of ductile cast iron against alumina. Journal of Tribology, 118, 748-752.

Renaud, Y., Renard, L., Gaspard, C., Allen, F., 1989. Laser textured sheets for deep drawing application. Iron & Steel Society 25, 415-425.

Schulze, K.-R. and Keitel, S., 1988. EB hardening, remelting, and alloying of surfaces. In: Contré, M. (ed), Proceedings of the 4th International Colloquium on Welding and Melting by Electrons and Laser Beam (CISFFEL), Cannes, France, (Doc/CEN, Saclay, France, 1988), pp. 505-513.

Selvan, J. Senthil, Subramanian, K., Nath, A.K., 1999. Effect of laser surface hardening on En18 (AISI 5135) steel. Journal of Materials Processing Technology, 91, 29-36.

Sridhar, K., Katkar, V.A., Singh, P.K., Haake, J.M., 2007. Dry sliding friction wear behaviour of high power diode laser hardened steels and cast iron. Surface Engineering, 23 (2), 129-141.

Xue, L., Islam, M.U., McGregor, G., 1999. Dot matrix hardening of steels using a fiber optic coupled pulsed Nd:YAG laser. Materials and Manufacturing Processes 14, 53-65.

Captions for figures

Figure 1 Typical optical microscopic images of laser treated spots on the ground AISI O1 steel surface at different energy density levels. The laser processing parameters were as follows: pulse energy 25 J/pulse, pulse duration 20 ms and defocus distances of (a) +11.4 mm, (b) +12.4 mm, and (c) +14.0 mm.

Figure 2 Cross-section view of microstructure of a laser treated sample (25 J/pulse, 20 ms pulse duration, defocus +11.4 mm).

Figure 3 SEM microstructures within the laser treated layer in (a) melting zone and (b) transformation hardening zone.

Figure 4 Hardness distribution across the diameter of a laser treated spot (polished substrate surface, laser treatment parameters: 25 J/pulse, 20 ms pulse duration, defocus +12.4 mm).

Figure 5 Effect of defocus distance on hardness of laser treated AISI O1 steel.

Figure 6 Typical variations of (a) hardening zone diameter and (b) melting zone diameter as a function of laser defocus distance at different pulse durations (pulse energy = 25 J/pulse).

Figure 7 Effects of substrate surface finish on variation of transformation hardening zone and melting zone diameters during pulsed laser surface treatment.

Figure 8 Processing parameter maps for discrete laser spot transformation hardening of AISI O1 tool steel at laser pulse energy levels of (a) 15 J/pulse, (b) 20 J/pulse, and (c) 25 J/pulse.

Figure 9 Variation of maximum diameter of hardening zone with no surface melting that is achievable at given pulse energy levels as a function of laser pulse duration.

Figure 10 Effect of laser pulse duration on area ratio of hardening zone to overall laser heat affected area at different laser pulse energy levels.

Figure 11 Variation of hardness in the transformation hardening zone as a function of laser pulse duration on samples treated under conditions along the surface melting/hardening boundary as given in Fig. 8c for pulse energy of 25 J/pulse.

Figure 12 Relationship between diameter and depth of white layers formed on AISI steel substrate after single pulse laser treatment at the different pulse energies: (a) 15 J/pulse, (b) 20 J/pulse, and (c) 25 J/pulse.