Abstract
Ultra-hard materials that are chemically inert and thermally stable at high temperatures are desirable for enhancing machining and wear performance in demanding chemical and thermal environments. Single and polycrystalline diamonds are the hardest tool materials; however, at high temperatures, diamond reacts with ferrous alloys, losing its chemical inertness and thermal stability. In contrast, cubic boron nitride (cBN) has exceptional chemical and thermal stability but has much lower hardness (35-45 GPa). Increasing the hardness of BN is expected to fill the property gap in state-of-the-art tool materials as shown and to generate huge industrial interest for meeting the stringent design requirements such as machining optical surfaces and reducing the cost and time for machining ferrous materials. A novel laser/waterjet heat treatment (LWH) process is investigated to enhance the surface hardness of a dual phase boron nitride (BN) material composed of 50% cubic and 50% wurtzite phases. Results indicate that experimentally measured hardness increase is dependent on the processing parameter such as laser fluence and overlap between heat treatment passes. Statistical analysis is carried out to identify the processing parameter that result in maximum hardness increase.

Keywords: Binderless cBN, Composite wBN/cBN, Laser Heat Treatment, Hardness.

1 Introduction
Superhard materials are widely used in many applications as cutting tools, abrasives, polishing materials, wear-resistant, and protective coatings. Diamond is considered to be the hardest material on the earth because of its short bonds and tetragonal crystal structure. Diamond has a short bond length made of carbon atoms linked together in a face-centered cubic (FCC) lattice structure. Each carbon atom is linked with four other carbon atoms in regular tetrahedrons, creating a cubic lattice with tremendous strength in all directions that forms an incredibly solid crystal structure (Veprek, Argon, and Zhang 2010). However, diamond also has limitations in thermal and chemical stability for
example chemical reactivity causes diamond to react with ferrous materials to produce iron carbide. This has inspired researchers to search for new superhard materials from cubic boron nitride, heterodiamond and other materials that have similar binding structure as diamond but have higher chemical and thermal stability. Cubic boron nitride (cBN), the second hardest material on the earth (Solozhenko et al. 2009), has a similar microstructure as diamond. Although cBN has good mechanical properties, chemical inertness and thermal stability, it cannot replace diamond as its hardness is well below that of diamond. Thus, searching for new superhard materials is not only of great scientific interest, but also of great practical value.

In order to find the most effective superhard materials, we should know what makes materials hard. In diamond, tetrahedral bonded sp3 carbon atoms form a three dimensional high symmetry network (Veprek, Argon, and Zhang 2010). In addition, the bond length is short as carbon is a light element. Thus, when we look for the superhard materials, light elements, such as boron, carbon, and nitrogen are considered (Brazhkin, Lyapin, and Hemley 2002). These elements are capable of forming three-dimensional rigid lattices with short covalent bonds. Moreover, in order to guarantee the materials resistance to compressive loads, elements with very high densities of valence electrons are considered. With these ideas, the search of new superhard materials has focused on the synthesis of range of materials composed of light elements and some of these superhard materials are plotted with respect to their measured Vicker’s hardness in Figure 1.

![Figure 1. Vicker's hardness of some superhard materials. It should be noted that, the hardness values of materials may depend on the sample quality. For example, the hardness of diamond depends on the quality and purity of the crystal (Vepřek 1999).](image)

Carbon nitride (C$_3$N$_4$) is theoretically predicted to have hardness approaching that of diamond (He, Bhole, and Chen 2008). However, after three decades of research studies, there is no synthetic sample of C$_3$N$_4$ that has validated this hardness prediction (Haines, L, and Bocquillon 2001). Boron carbide (B$_4$C) is a superhard technical ceramic with an extreme Vicker's hardness of 30 GPa (Ulrich et al. 1998). B$_4$C was thought to be one of the potential superhard materials that could replace diamond in the future, but its hardness decreased from 30 GPa at room temperature to around 20 GPa at 1000 degrees Celsius(Thévenot 1990). Thus, B$_4$C could not be considered as a new candidate superhard
material to replace diamond (Thévenot 1990). Metal borides are a binary compounds with elements from each of the main groups of the periodic table (Tyne 1965). Unlike carbon-based materials; metal borides can be created in large synthetic quantities under ambient conditions (Jonathan B. Levine, Tolbert, and Kaner 2009). Osmium diboride (OsB₂), an example of metal boride, has a high bulk modulus (395 GPa) and therefore is considered as a potential superhard material. However, its maximum Vicker's hardness has been measured to be only 37 GPa (Gou et al. 2009). Rhenium diboride (ReB₂), another example of metal borides, was also considered as a potential superhard material because of its high calculated values of bulk modulus and shear modulus (J.B. Levine et al. 2010). However, Dubrovinskaia, Dubrovinsky and other researchers have measured and reported the Vicker's hardness of ReB₂ to be only 19 to 17 GPa at a range of load from 3 N to 49 N (Dubrovinskaia, Dubrovinsky, and Solozhenko 2007). Thus, OsB₂ and ReB₂ could not be considered as potential superhard materials to reach diamond hardness. Ceramic and cermet machining tool materials, such as tungsten carbide (WC), silicon nitride (Si₃N₄), and silicon carbide (SiC), as hard materials has been widely used in tooling industry. They all have high wear-resistant but their Vicker’s hardness are 14 GPa (Liu and Li 2001), 34GPa, and 24.6GPa (Yin et al. 2004) for WC, Si₃N₄, and SiC respectively. Thus, they could not be the potential superhard materials to replace diamond tools.

Despite most previous works’ efforts to create superhard materials by synthesizing superhard materials, many opportunities still remain unexplored. For example, there is a design of the thermally stable and chemically inert nanoscale grain size cBN/wBN composite with increased hardness through microstructure refinement and nanotwinned grains (Li, Sun, and Chen 1996; Li, Sun, and Chen 2014; Huang et al. 2014). However, the synthesis of specialized microstructures is challenging and involved. The Hall-Petch relation states that the material hardness has a negative relationship with its grain size which gives us an opportunity to enhance the material hardness. Nanograined diamond has been successfully synthesized from pure graphite at 2300 to 2500°C and 12 to 25 GPa. It’s grain sized controlled in 10 to 30 nm with a high Koop hardness of 110 to 140 GPa (Irifune et al. 2003). However, the oxidation temperature of the nanograined diamond still very low (about 680°C in air) (Solozhenko, Kurakevych, and Le Godec 2012). Demazeau (Demazeau, Biardeau, and Vel 1990) used magnesium fluoronitrides as flux-precursor to convert hBN into cBN under high temperature and high pressure (HTHP). However, the synthesized cBN has flux as chemical impurity that reduced the physical properties of it. Many physical as well as chemical processes have been explored in order to synthesize cBN films or cBN/wBN composites. Nevertheless, these different processes is often very difficult to reproduce. Therefore, surface treatment based approaches that can be used to enhance the hardness of commercially produced boron nitride tools are highly desired as they can be easily integrated into conventional manufacturing processes.

In order to achieve enhanced hardness in commercially produced cubic boron nitride materials, a novel laser/waterjet heat treatment (LWH) was performed on cBN/wBN composite, and a preliminary study was conducted to find that the hardness of the cBN/wBN composite could reach the hardness of diamond (A. Melaibari, Molian, and Shrotriya 2012; A. A. Melaibari et al. 2016). The new discovery of cBN/wBN composite whose hardness matches the hardness of diamond can have vast implications in the tooling industry. Hence, in this paper, a series of experiments on LWH treatment of dual phase cBN/wBN tools was designed in order to identify the optimum processing parameters that result in maximum enhancement of surface hardness.

In previous studies Melaibari et al. (A. A. Melaibari et al. 2016) have designed a laser/waterjet heat treatment (LWH) and applied to enhance the surface hardness of dual phase 50% cubic boron nitride (cBN) and 50% wurtzite boron nitride (wBN) tool materials to match that of polycrystalline diamond tool materials. In the LWH process, a shaped laser beam was scanned across the sample to
heat the surface material below the melting point and a tandem waterjet followed the laser beam to quench the heated material. Fig 2 shows a schematic of continuous wave CO₂ laser/waterjet nozzle system where the beam is separated from waterjet for a distance of 2 to 6 mm. The LWH processing consisted of surface heating the cBN samples using a low power continuous wave CO₂ laser beam followed by tandem waterjet quenching of the laser beam path to cause stress-induced microstructural changes. The low laser fluence prevented melting, scribing, or cutting of boron nitride. During LWH processing, maximum surface temperatures after laser irradiation for a duration of 0.02 s were estimated to be around 1000-1300 K indicating that the material surface is heated at approximately 50,000 K/s and rapidly quenched back to room temperature (A. A. Melaibari et al. 2016). Localized heating of the surface leads to development of large compressive stresses (~2 GPa) in the laser-heated area. Hence, the key characteristics of LWH are the thermomechanical loading associated with rapid heating and cooling that generates non-equilibrium microstructures in the treated samples. Experimental results showed that surface treatment over a narrow range of laser fluence (35 to 55 J/m²) results in enhanced hardness of dual-phase materials. LWH treatment of boron nitride tools with laser fluence greater than 55 J/m² results in spallation damage on sample surface due to phase transformation of cBN to hexagonal boron nitride. While no change in cBN surfaces was observed for surface treatment below laser fluence of 35 J/m².

![Figure 2. Schematic of LWJ heat treatment process](image-url)

Given this narrow range of the laser fluence associated with damage free hardness enhancement, experiments were conducted to the study on the influence of repeated LWH treatment on hardness enhancement in dual phase boron nitride materials. The laser beam was scanned in a raster pattern to treat the sample surface. The overlap between adjacent scan lines in the raster pattern was varied to investigate the influence of repeated LWH treatment on the hardness enhancement and to identify the processing parameters associated with maximum enhancement in surface hardness.
2 Method

A continuous wave CO2 laser (Laser Spectra Physics 820) was employed to conduct the LWH experiments with a laser power of 180 W, a spot size of 1 mm, and with a laser fluence of 33 J/mm$^2$. The sample was LWH treated by scanning the sample surface in a raster pattern with different overlaps between adjacent scans to study the influence of repeated laser heating and cooling. The overlap percentages of 0%, 20%, 50%, 70% and 100% were investigated.

The materials used in this study were binderless dual phase cBN/wBN with iron oxide as the impurity. The samples were synthesized to obtain a cBN content between 45% to 55% with wBN phase being the remainder. In order to identify the change of the sample’s hardness, Vicker’s microhardness tests were taken before and after heat treatment and the influence of overlap percentage on the hardness enhancement was investigated using a statistical regression analysis.

Based on previous study (A. A. Melaibari et al. 2016), low laser power fluence (1 mm spot size) was used on following experiments to prevent melting, scribing or cutting of boron nitride. In order to find the relationship between laser beam overlap and hardness improvement, the experimental study was designed by using randomized complete block design (RCB). RCB based experimental design procedure are able to determine a relationship between independent input process parameters and output data (process response) (Aouici et al. 2012). In this paper, laser beam overlap percentage is identified as the factor that affects the response—cBN/wBN composite hardness change ratio. Five levels of overlap percentages were used as the factor and the range of the factor was selected based on preliminary research and experiment condition. The factor and its levels are presented in table 1 and the experimental layout plan is given in table 2.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overlap percentage between adjacent LWH treatment passes</td>
<td>0%</td>
</tr>
</tbody>
</table>

**Table 1:** Factor and levels

Note: 0% overlap indicates the 2nd laser beam is 1 mm (laser beam spot size is 1 mm) away from the 1st laser beam. And 20% overlap indicates the 2nd laser beam is 0.8 mm away from the 1st laser beam and so on.

Two pieces of binderless dual phase 50%wBN/50%cBN composites were used as work materials. The average hardness of each piece of cBN/wBN composite was 38 GPa and 39 GPa respectively. Ten areas for surface heat treatment were demarcated on two work pieces, where work piece 1 has two areas and work piece 2 has eight areas, and numbered from 1 to 10 (see Figure 3). Finally each of these 10 areas was LWH treated with a randomly assigned overlap percentage as shown in Table 2.
Indentation hardness tests were performed using a Tukon microhardness tester with a Vicker’s diamond pyramid indenter. The load was set at 1 kgf (9.8N), and the test duration was set at 30 seconds. Length measurements were made along the diagonal of the indentations using a high resolution (± 1 µm) optical microscope and optical profilometer to ensure that no fracture had occurred in the indentation zone. Vicker’s hardness was then calculated using the relationship:

\[ HV = \frac{\text{1.8544L}}{d^2} \]  

(1)

where L is the load (kgf), and d is the average length of the two diagonals of the indentation.

Ten hardness tests were obtained at each area before and after LWH treatment. All indentation hardness can be considered reliable because no visible plastic deformation or damage of indenter diamond tip were observed after the measurements of hardness (Figure 4). In order to maintain precision while measuring the length of indentations, the indentation optical images were taken by optical microscope. The length of indentations were measured on optical images by a Java-based image processing program known as ImageJ.

![Figure 3: Layout of heat treatment areas](image)

**Table 2: Experiment design**

<table>
<thead>
<tr>
<th>Experiment design</th>
<th>Overlap percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>0%  20%  50%  70%  100%</td>
</tr>
<tr>
<td>8 and 10</td>
<td>3 and 6</td>
</tr>
<tr>
<td>2 and 4</td>
<td>1 and 5</td>
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<tr>
<td>7 and 9</td>
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</table>

![Figure 4: The 100 X magnification images of square pyramid diamond tip before (A) and after (B) hardness measurements](image)
3 Results

Visual examination of LWH treated surfaces with 0%, 20%, and 50% overlap revealed only a color change from light-absorbing black/gray to transparent white in areas along the laser scan lines. Such an effect is ascribed to a change in crystal morphology following Sachdev’s classification of the crystalline morphology of cBN according to color, size, and transparency (Vepřek 1997). A transparent cBN of white to amber color implies tetrahedral crystal morphology (as opposed to octahedral) with small grain size and loss of boron. It may be noted that the color may also be caused by inclusions, dopants or defects. The formation of transparent white color of the cBN has previously been associated with enhancement of surface hardness (A. Meliaibari, Molian, and Shrotriya 2012).

Visual examination of LWH treated surfaces with 70%, and 100% overlap revealed areas of spallation induced damage (about 200 to 400 micron wide) along the laser scan lines while the undamaged surface showed a color change similar to the LWH treated areas with lower overlap percentage. A SEM image of the spallation induced surface damage is shown in Figure 5 and shows these damages were narrower than laser beam radius and were oriented along the laser scan directions.

![Figure 5: The peel off region on 70% overlap LWH treated sample](image.png)

Measured Vickers hardness before and after LWH treatment for surface treated with different laser beam overlap percentage are plotted in Figure 6. The bars around each point show the standard deviations of the 15 different measurements performed for each data point. As shown in Figure 6, the hardness of the untreated sample was found to be 40 ± 4 GPa, 42 ± 9 GPa, 37 ±4 GPa, 38 ± 4 GPa, 36 ± 4 GPa, 36± 5 GPa, and 40 ± 4 GPa for 0% on sample 2, 20% on sample 2, 50% on sample 2, 50% on sample 1, 70% on sample 1, 70% on sample 2, and 100% on sample 2, respectively. After LWH treatment, the surface hardness on LWH with 0% on sample 2, 20% on sample 2, 50% on sample 2, 50% on sample 1, 70% on sample 1, 70% on sample 2, and 100% on sample 2 are found to be 51 ± 6 GPa, 54 ± 10 GPa, 61 ± 11 GPa, 65 ± 14 GPa, 66 ± 11 GPa, 53 ± 12 GPa, and 54 ± 4 GPa, respectively. The LWH treatment resulted in maximum increase of 169% of the initial hardness in area treated with LWH with 50% overlap on sample 1. Another indicator of the increased hardness of the LWH treated sample was the hardness distribution on the laser beam track. Because the laser beam created by Laser Spectra Physics 820 is a Gaussian beam, the power density is not uniform along the
entire beam path. Therefore, the laser beam energy irradiated on the cBN/wBN composite was not uniform along the width of the laser beam. On 0%, 20%, and 50% overlap LWH treated sample, hardness tests on the center of each laser track were slightly higher than those on the edge of the laser track. This hardness variation in the scan width resulted in the observed larger standard deviation in the LWH treated surfaces (Fig 6).

![Figure 6](image_url)

**Figure 6:** Vicker’s indentation hardness tests data of binderless cBN/wBN composite: 0%(S2B) means 0% overlap on sample 2 before LWH.

The maximum hardness change ratio was observed on 50% overlap area that is 160% over than the untreated area. The minimum hardness change ratio was observed on 0% overlap area that is only 30% over the untreated area. In spite of 155% (very close to 50% overlap area) over the untreated area hardness in our data, the 70% overlap could not be considered the good laser parameter for future studies. The hardness measurements on 70% overlap areas were taken only on undamaged surface where similar with 50% overlap treated area. According to our previous studies (A. A. Melaibari et al. 2016), the hardness on spall region might decrease compare with untreated material.

4 Discussion

In order to find the relationship between laser beam overlap and hardness improvement, a statistic model using randomized complete block design (RCB) was developed. A variance analysis of the hardness change ratio was made with the objective of analyzing the influence of laser beam overlap (OL) and sample property (initial hardness) difference (S) on the result. Table 3 shows the result of ANOVA for hardness change ratio. This analysis was conducted for a 10% significance level, i.e., for a 90% confidence level. This ANOVA table shows that laser beam overlap has a significant effect on the hardness change ratio. But the sample property difference has an insignificant effect on the hardness change ratio. Therefore, in the further studies, we will focus only on the effects of laser beam overlap.
Table 4 shows the statistical comparison results of Vicker’s hardness tests of binderless 50%cBN/50%wBN as a function only of the laser beam overlap percentage. The highest hardness change was observed for 50% overlap that is 160% of the original hardness, and the lowest hardness change ratio was observed on 0% overlap that resulted in enhanced hardness of only 130 % of the original hardness. Compare with 50% overlap, 70% and 100% overlap hardness change ratio are relatively smaller. The smaller enhancement in surface hardness may be due to the spalling surface damage (shown in Figure 5). Raman characterization of the LWH treated surface has shown that there is minimal changes in the phase composition in undamaged LWH treated areas but the spallation damage surface shows a phase transformation of cBN to the hexagonal boron nitride (hBN) (A. A. Meliabari et al. 2016). The hBN phase has a larger lattice volume and is significantly lower in hardness as compared to cBN and wBN phases. The volumetric expansion associated with cBN to hBN transformation may have resulted in the surface damage and observation of lower hardness enhancement at 70% and 100% overlap. In order to identify the overlap percentage associated with maximum enhancement, the hardness change ratio was fitted to statistical regression model of the overlap percentages as shown in Figure 7.

\[ \text{Ratio} = 1.307 + 0.485OL - 0.871(OL - 0.48)^2 - 1.653(OL - 0.48)^3 \]  

where OL is the overlap percentage value.

The predicted values of ratio are compared with the corresponding experiment values that was depicted in Figure 7.
According to the statistical linear regression model, the OL value of 65-66% may result in maximum enhancement of surface hardness due to LWH treatment. In the current paper, the study of laser beam overlap effect on the hardness change ratio of cBN/wBN composite has led to a statistical model based on the experiment results. LWH experiments showed that the hardness of 50% cBN/50% wBN composite increase up to 160% of the original hardness value however this increase is not as dramatic as 200% of the original hardness reported in our previous investigations (A. A. Melaibari et al. 2016). The difference in hardness enhancement may be due to the differences in phase compositions and presence of microstructural defects in the samples. The samples used in the current study had an relative lower initial hardness of 39-40 GPa as compared to the initial hardness of 48 GPa for samples used in the earlier study (A. A. Melaibari et al. 2016). The difference in lower hardness may be due different phase composition cBN/wBN content and more microstructural defects. These results indicate that influence of sample composition on LWH induced hardness enhancement needs to be investigated. We are currently conducting experimental investigations to identify the influence of different wBN phase content on hardness enhancement and these results will be reported in a forthcoming article.

A finite element analysis was applied to estimate the thermal fields induced in the sample during the LWH processing. An axisymmetric finite element model was used to model the localized heating due to the incidence of laser beam followed by the quenching of the heated material surface due to the water-jet. Water quenching leads to rapid decrease of temperature in the circular zone heated by low-power laser therefore the heating and subsequent cooling associated with LWH processing can be modeled as an axis symmetric problem. The Gaussian profile of the laser beam is approximated as a surface heat source whose intensity at radial distance \( r \) from center is given in Eq. (3):

\[
I(\mathbf{r}) = I_0 \exp \left( \frac{-2r^2}{w^2} \right)
\]

Where \( I_0 \) is the intensity at the center of the beam, \( \alpha \) is the absorption coefficient, and \( w \) is the diameter of the laser beam spot. The absorption coefficient was chosen to be 0.75 (A. Melaibari, Molian, and Shrotriya 2012). The laser intensity at the center of the beam was calculated based on the laser fluence used in the laser heat treatment experiment. The duration of laser spot interaction with sample surface was calculated to equal the duration that a laser beam is incident at a material point during experiments. Thermal quenching due to the waterjet was modeled using convective heat transfer coefficient of 10,000 W/m²K such that the sample surface is rapidly cooled down to room temperature on the action of waterjet (A. Melaibari, Molian, and Shrotriya 2012). Finite element
analysis package ABAQUS was utilized to compute the temperature and stress fields associated with LWH experiments. The boundary conditions and geometry of the FEM model are shown in Figure 8. The thermal and mechanical properties used to model pCBN response are listed in Table 5. The finite element mesh was refined till the computed temperature and stress field became independent of the element size.

![Figure 8: Axissymetric finite element model with boundary conditions](image)

The computed temperature and stress field in the samples at the end of laser irradiation is plotted in Figs 9(a) and (b), respectively. The contour plots show that material near the irradiated surface is heated while the rest of the material remains at room temperature. The localized heating of the sample surface also led to development of large compressive stresses in the laser-heated area. The stress field in the sample dissipated as the sample is rapidly cooled down with the waterjet.

![Figure 9: Contour plots of A) temperature and B) radial stress fields at the instant of maximum temperature during LWJ treatment.](image)

<table>
<thead>
<tr>
<th>Density (g/cm³)</th>
<th>Thermal Conductivity (W/mK)</th>
<th>Specific Heat Capacity (J/kg°C)</th>
<th>Poisson’s Ratio</th>
<th>Young’s Modulus (GPa)</th>
<th>Thermal Expansion Coefficient (1/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>200</td>
<td>920</td>
<td>0.15</td>
<td>710</td>
<td>5.6 x 10^-6</td>
</tr>
</tbody>
</table>

Table 5: Thermal and mechanical properties of PCBN

During LWH surface treatment, the temperature of the surface increased rapidly during laser heating and attained a maximum value at the end of the laser irradiation. After the laser heating, the sample surface was rapidly cooled due to the waterjet quenching. The computed temperature and stress field in the samples at the end of laser irradiation is plotted in Figs 9(a) and (b), respectively. The contour plots show that material near the irradiated surface is heated while the rest of the material remains at room temperature. The localized heating of the sample surface also led to development of large compressive stresses in the laser-heated area. The stress field in the sample dissipated as the sample is rapidly cooled down with the waterjet.
The temperature and stress calculation indicate that material under laser irradiation is subjected to a temperature rise of 700K and compressive stresses of 1 GPa during laser heating and the heated material is rapidly quenched to room temperature under the waterjet action. The combined action of high temperatures and high compressive stresses may lead to microstructure refinement that results in hardness enhancement observed in the current experiments. The maximum increase in temperature on the sample surface are plotted in Figure 10 as a function of distance from laser beam center. This shows that for 0% the sample points are heated to maximum temperature when they lie under the laser beam scan but as the beam moves away the sample is only subjected to rise of 400K in subsequent passes. The magnitude of rise in subsequent passes increases monotonically as the overlap percentage is increased from 0% to 100%. At 70% overlap, points along the sample surface are subjected to as much as three laser irradiation during the raster pattern scan. During each of these scans the laser irradiated surface is subjected to temperature rise above 650 K and this repeated heating of the sample surface may have resulted in spallation surface damage.

Figure 10: Maximum temperature rise along the surface under laser beam during LWH treatment.

5 Conclusion

Laser-waterjet treatment composed of tandem laser heating and waterjet quenching is utilized to increase the hardness of dual phase boron nitride based material such that hardness of treated surface is increased to 160% of the initial hardness. The LWJ treatment is able to achieve the maximum hardness increase for treatment with 33 J/mm² with 50% overlap between adjacent passes during raster pattern laser scans. LWH treatment with same laser fluence but overlap percentage greater than 70% results in spallation damage. Numerical analysis of the LWH treatment shows that the microstructure refinement is associated with heating the surface above 900 K and rapidly quenching the surface. A statistical regression model was developed to find the optimal laser beam overlap percentage associate with maximum hardness change during LWH treatment.

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