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Research Article

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Improvement of Plasma Nitriding Efficacy of Alloy Steel by Laser Peening

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Abstract

Laser peening is an advanced technology used for improving metallic material properties. These improved properties are achieved through induced compressive residual stresses. This will enhance the useful service life of products in the intended applications. Laser peening is also useful for assisting and improving further processing operations involved in the fabrication phase of the components. Alloy steels are utilized in engineering applications owing to their superior strength properties. But these alloy steels are found lacking in wear resistance. Plasma nitriding can be used for improving the case hardness of the materials which tend to fail due to wear during their service life. Laser peening can be performed as preprocessing stage for the improvement of the plasma nitriding effectiveness. The microhardness results of plasma nitrided samples with laser preprocessing show considerable improvement in hardness levels compared with the un-peened sample. This is achieved through an overlap rate of 40% of laser spot size during the laser peening operation. The increase in case-hardened depth was revealed by the optical microscopy analysis. And it was observed that the case-hardened depth increased by up to 125%.

Keywords

Laser peening, Plasma nitriding, Alloy steel, Microhardness, Case hardened depth

Introduction

The materials involved in engineering applications require custom-built properties to cater to their intended purposes [1-4]. Most of the materials fail by the premature worn-out conditions of the functional components [5]. Over the past decades, the evolution of various case hardening techniques has led to the minimization of wear-induced failures by increasing the case hardness of the materials. Alloy steels, like stainless steel, are chosen for applications that require high strength to withstand failure stress levels. They also can be used in corrosive environments [6]. Even though they have higher strength, they may fail during operation due to poor wear characteristics. Therefore, case hardening techniques can be implemented to improve the surface hardness of these materials [7]. Based on the above-mentioned advantage, stainless steel also includes case hardening in the process stage to improve the wear characteristics. Plasma nitriding [8] is one of the case hardening techniques that have salient advantages over other techniques. Particularly, a smooth and pore-free nitrided layer is achieved with plasma nitriding when compared with gas nitriding.

Nowadays, Laser peening [9]is emerging as a potential process to improve the material properties required for critical functional applications. Laser peening can be mainly used for improving service life by imparting compressive residual stresses [10], which is mainly responsible for offsetting the crack initiation stress levels during the operation. A very short-pulsed laser is irradiated on a sacrificial layer, which is adhered to the surface at the desired location of the component, where the laser tends to form plasma owing to high-intensity levels of the laser. This plasma can be enclosed by a confining medium such as water or glass over the sacrificial layer. Finally, a high-pressure shock wave is generated from the confinement of the continuous plasma. This shock wave will plastically deform the material's surface, and the resultant resistance to deformation will create compressive residual stresses on the surface. The depth of the affected surface is dependent on the parameters chosen, especially the laser overlap rate. This present work tries to analyze the effect of laser peening as a preprocess to the plasma nitriding of 17-4 PH stainless steel.

Materials and Methods

Material

The 17-4 PH stainless steel was chosen as the work material for the present investigation. Most high-strength engineering applications like gears use this material owing to its remarkable strength and corrosion resistance. The chemical composition of 17-4 PH stainless steel material is as follows: 0.037% C, 15.39% Cr, 4.44% Ni, 3.26% Cu, 0.24% Si, 0.32% Mn, 0.33% Nb + Ta, 0.018% P, 0.002% S, remaining Fe. The test coupon size used for this study was 10 mm x 10 mm x 5 mm. The mechanical properties required for the computation of the laser peening parameter are Yield strength (1255 MPa) and Poisson's ratio (0.29). The prepared samples are shown in figure 1.

Laser peening

The plastic deformation of a material is achieved through laser peening by exceeding the material's Hugoniot elastic limit (HEL). The Nd: YAG pulsed laser source with a wavelength of 1064 nm and duration of 15 ns was used as the peening medium. The PVC insulation tape of 100 μm was used as the sacrificial layer, and water was used as the confining medium. The laser intensity was calculated from Eq. (1) and Eq. (2). Based on the laser intensity, the diameter of the laser spot size was fixed as 1 mm. The laser overlap rate and the number of impact layers were varied in this study which is in line with the parameter values observed in the available literature. The experimental setup is shown in figure 2. The summarized parameters are shown in table 1. The untreated sample was named UPN. The samples that were laser peened prior to plasma nitriding were named LPN-x, where x refers to the sample number.

$$\sigma_{HEL} = \frac{1-v}{1-2v}\sigma_y \tag{1}$$

Where,σ_{HEL} represents Hugoniot elastic limit, σ_y denotes the yield strength of the material, and *v* denotes Poisson's ratio.

$$P = \sqrt{\frac{\alpha}{2\alpha+3}}ZI_0 \tag{2}$$

Where, P denotes shock wave pressure in GPa which lies between 2 - 2.5 times the HEL, α denotes efficiency coefficient (0.25), Z denotes composite shock wave acoustic impedance of steel and water (0.32 x 10^6 g/cm^2), and I_0 denotes laser intensity in GW/ cm^{2,} which is calculated from the Eq. (3).

$$I_0 = \frac{4E}{\pi d^2 \tau} \tag{3}$$

Where, E denotes the energy of a laser per pulse, d denotes the diameter of the laser spot, and τ denotes pulse duration.

Plasma nitriding

After Laser peening of the LPN samples, plasma nitriding was done on them in a chamber at a pressure level of 5 mbar.

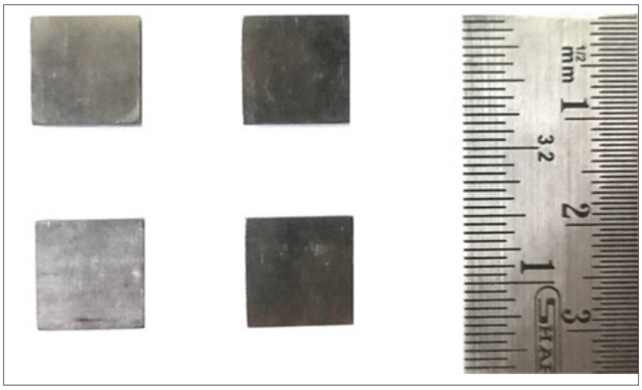

Figure 1: Samples made for laser peening experiment.

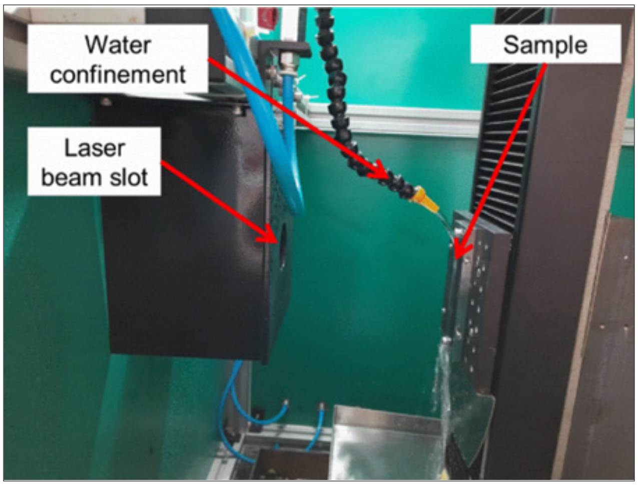

Figure 2: Laser peening experimental setup.

Table 1: Summarized laser peening parameters.

Parameter	Values				
Shock pressure (GPa)	4.7				
Intensity (GW/ cm^2)	9.6				
Diameter of the laser spot (mm)	1				
Overlap rate	0%			40%	80%
Number of impact layers	1	2	3	1	1
Sample identification	LPN-1	LPN-2	LPN-3	LPN-4	LPN-5

The chamber was filled with a hydrogen and nitrogen gas mixture, and it was maintained at a ratio of 1:4. The processing temperature and duration maintained over the process were 500 °C and 10 hours, respectively. The samples were cleaned by hydrogen sputtering before the plasma nitriding process.

Testing methods

The Laser peened samples after plasma nitriding was cut, mounted, and polished by SiC emery papers, alumina, and diamond. The microhardness test was performed on the cross-section of these samples by using a microhardness tester (QNESS A+, Austria). The interface and the thickness of the plasma nitrided layer were measured by using an optical microscope (ZEISS Axio Lab.A1, Germany).

Results and Discussion

Microhardness analysis

The microhardness analysis performed on the cross-section of the plasma nitrided samples is shown in figure 3. It was observed that the results of laser-peened samples have microhardness values more than the untreated plasma nitrided sample (UPN). The sample with a 40% laser overlap rate (LPN-4) had higher hardness values within the effective depth of the plasma nitrided layer compared to the unpeened sample. Due to the requirement of maintaining minimum indentation space between subsequent indents during the hardness measurement, it was not possible to obtain more hardness readings closer to the interface between the nitrided layer and base metal. Hence it was not possible to use the microhardness values as an indirect method to measure the case-hardened depth of the nitrided layer. Therefore, the optical microscopy analysis was performed for the measurement of plasma nitrided layer thickness.

Optical microscopy analysis

The cross-sectioned and polished surface of the LPN samples was examined through an optical microscope. The interface between the base metal and plasma nitrided layer was clearly distinguished and is shown in figure 4. The thickness of the nitrided layer on the LPN samples was measured. It was observed that the LPN-4 sample which was laser peened with a 40% laser overlap rate had more thickness of plasma nitrided layer compared with other samples. The observed thickness in the LPN-4 sample was 125% more than the untreated sample. The thickness of the plasma nitrided layer for the different samples is reported in table 2.

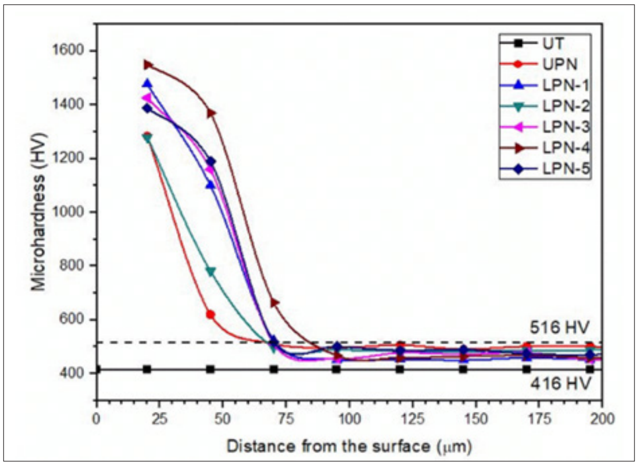

Figure 3: Microhardness analysis of samples.

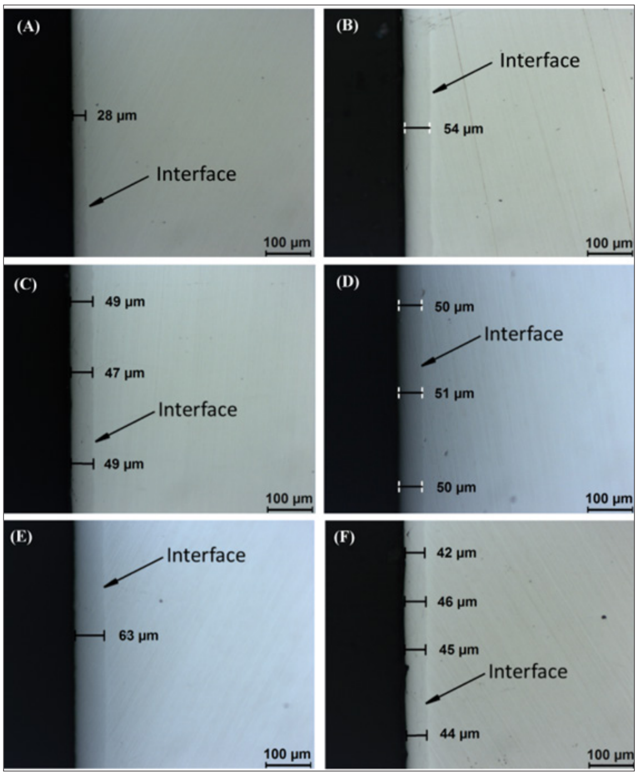

Figure 4: Optical microscopy analysis of plasma nitrided sample. **(A)** Untreated sample (UPN), **(B)** Single layer impact (LPN-1), **(C)** Double layer impact (LPN-2), **(D)** Triple layer impact (LPN-3), **(E)** 40% overlap rate (LPN-4), and **(F)** 80% overlap rate (LPN-5).

Table 2: The measured thickness of plasma nitrided layer.

Sample identification	UPN	LPN-1	LPN-2	LPN-3	LPN-4	LPN-5
Measured Thickness (µm)	28	54	48	50	63	44

Conclusions

The following conclusive remarks were obtained in light of the results of the present investigation:

- It was observed that the laser peening treatment improved the effectiveness of the plasma nitriding process in terms of both microhardness and case-hardened depth.
- Improved hardness values were obtained on the plasma nitrided sample which was preprocessed with a 40% laser overlap rate compared to the untreated sample.
- From the optical microscopy results, the laser-peened sample with a 40% laser rate has a 125% increase in case-hardened depth compared with the untreated sample.
- Therefore, 40% laser overlap rate was found to be the optimum parameter in the laser peening process in order to obtain higher case-hardened depth during the plasma nitriding process of 17-4PH stainless steel.

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Conflict of Interest

The authors declare no conflict of interest that are relevant to the content of this article.

Credit Author Statement

Avinash S: Methodology, Experimentation, Investigation, Writing - original draft preparation; Vineet Kumar Yadav: Writing - review and editing, Supervision; Tony M Shaju: Writing - original draft preparation; K Vijayan: Writing - review and editing; Pradeep K: Writing - review and editing. All the authors read and approved the manuscript.

References

1. Ganesh P, Sundar R, Kumar H, Kaul R, Ranganathan K, et al. 2012. Studies on laser peening of spring steel for automotive applications. *Opt Lasers Eng* 50(5): 678-686. https://doi.org/10.1016/j.optlaseng.2011.11.013
2. Kalainathan S, Sathyajith S, Swaroop S. 2012. Effect of laser shot peening without coating on the surface properties and corrosion behavior of 316L steel. *Opt Lasers Eng* 50(12): 1740-1745. https://doi.org/10.1016/j.optlaseng.2012.07.007
3. Heinz A, Haszler A, Keidel C, Moldenhauer S, Benedictus R, et al. 2000. Recent development in aluminium alloys for aerospace applications. *Mater Sci Eng A* 280(1): 102-107. https://doi.org/10.1016/S0921-5093(99)00674-7
4. Lu H, Ren Y, Chen Y, Zhu H, Xin Z, et al. 2021. Wear resistance of 20Cr2Ni4A alloy steel treated by laser shock peening and implantation of diamond nanoparticles. *Surf Coat Technol* 412: 127070. https://doi.org/10.1016/j.surfcoat.2021.127070
5. Gagg CR, Lewis PR. 2007. Wear as a product failure mechanism–overview and case studies. *Eng Fail Anal* 14(8): 1618-1640. https://doi.org/10.1016/j.engfailanal.2006.11.064
6. Yoo WD, Lee JH, Youn KT, Rhyim YM. 2006. Study on the microstructure and mechanical properties of 17-4 PH stainless steel depending on heat treatment and aging time. *Solid State Phenom* 118: 15-20. https://doi.org/10.4028/www.scientific.net/SSP.118.15
7. Liu H, Liu H, Bocher P, Zhu C, Sun Z. 2018. Effects of case hardening properties on the contact fatigue of a wind turbine gear pair. *Int J Mech Sci* 141: 520-527. https://doi.org/10.1016/j.ijmecsci.2018.04.010
8. Menthe E, Bulak A, Olfe J, Zimmermann A, Rie KT. 2000. Improvement of the mechanical properties of austenitic stainless steel after plasma nitriding. *Surf Coat Technol* 133: 259-263. https://doi.org/10.1016/S0257-8972(00)00930-0
9. Zhang XQ, Li H, Yu XL, Zhou Y, Duan SW, et al. 2015. Investigation on effect of laser shock processing on fatigue crack initiation and its growth in aluminum alloy plate. *Mater Des* 65: 425-431. https://doi.org/10.1016/j.matdes.2014.09.001
10. Kalentics N, Boillat E, Peyre P, Ćirić-Kostić S, Bogojević N, et al. 2017. Tailoring residual stress profile of selective laser melted parts by laser shock peening. *Addit Manuf* 16: 90-97. https://doi.org/10.1016/j.addma.2017.05.008