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Effect of Laser Shock Peening (LSP) Without Coating on the Surface Morphology and Mechanical Properties of Nickel Alloy

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This paper delineates the effects of low energy laser shock peening (LSP) without coating on Monel K-400 specimen. Comparative study of X-ray diffraction (XRD) analysis of the treated specimen with untreated specimen suggests the presence of compressive residual stress and grain refinement. The crystalline size has been calculated for peened and unpeened samples using the Scherrer's equation from the XRD data. The residual stress analysis was carried out using the XRD $\sin^2 \Psi$ method. The results indicate high amount of compressive residual stress has been induced in the specimen after the LSP process. The surface topography result dictates that there is a considerable increase in the surface roughness after the laser peening process. The hardness profile of the material was increased from a 144.5 to 150.7 HV.

Keywords: *Laser shock peening without coating (LSPwC); surface morphology; X-ray diffraction (XRD); residual stress; hardness*

1. INTRODUCTION

The use of nickel-copper alloys has dramatically increased in the field of marine engineering due its corrosion resistant properties. Monel K-400 which possesses high strength and durability over a wide-ranging temperature and its superb resistance to many corrosive conditions has made it an essential component in auto-

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motive as well as in aerospace[1-3]. Therefore, the alloy has been used extensively in many applications such as chemical processing equipment, gasoline and fresh water tanks, crude petroleum stills, valves and pumps, propeller shafts, marine fixtures and fasteners, electrical and electronic components, de-aerating heaters, process vessels and piping, boiler feed water heaters and other heat exchangers, and etc. [2,3]. Monel K-400 has an excellent mechanical property at subzero temperatures. Its strength and hardness upsurge with only slight enhancement of ductility-to-brittle transition even when refrigerated to the temperature of liquid hydrogen. This is in noticeable contrast to numerous ferrous materials which are fragile at low temperature in spite of their better strength [4].

Monel K-400 provides special resistance to hydrofluoric acid in all concentrations up to the boiling point. It is possibly the most resistant of all generally used engineering alloys. It is resistant to many methods of sulfuric and hydrochloric acids under reducing circumstances. Therefore, in order to add-up to these unique and excellent properties of Monel K-400 we make use of a process called laser shock peening (LSP) with respect to other processes like shot peening and ultrasonic peening [5]. In shot peening, we make use of a hard media (metal, ceramic, etc.), by accelerating the media at a high velocity towards the specimen surface which as a result induces plastic deformation and hence the compressive residual stress. The main drawback of this process is that the depths and magnitudes of residual stress are comparably less than that of laser peening [6]. In ultrasonic peening, we make use of an electro-mechanical method in order to generate shock waves, which are induced into the material by means of vibrating steel pins attached to a calibrated frequency controller. The disadvantage of using this method is that most ultrasonic peening are hand-held tools which possess difficulties with repeatability and consistency.

Laser shock peening LSP method has potential to improve the mechanical properties of Cu-Ni alloys, the present study has been done to basically understand the effects of laser shock peening of LSP on the deformation microstructure, hardness, residual stress, and in this Monel K 400 specimen. The results of all the characterization point out the effectiveness of the laser shock peening without coating (LSPwC) method for inducing elastic and plastic deformation in Cu-Ni alloy and thus enhancing its performance [1,2,4]. A variation of this method is the technique of LSPwC where the specimens are peened without a conventional coating [5-7]. Qiao Hongchao *et al.* have shown that beneficial changes in the specimen's microstructure have been caused due to LSP [4]. The present study focuses on the nickel based super alloy - Monel K-400 which possesses high strength and durability over a wide- ranging temperature and its superb resistance to many corrosive conditions has made it an essential component in automotive as well as in aerospace. The effects of LSP on the material have been extensively studied by Sano *et al.* [8].

LSP is an innovative and the most reliable technique to enhance the surface properties of a material by imparting deep compressive residual stress and enhancing the fatigue life since the LSP creates grain refinement by inducing plastic deformation [9]. LSP makes use of high energy laser beam to irradiate the ablative layer on the work piece which then vaporizes and converts into plasma after absorbing energy from the laser pulses. Owing to the restraining effect of the apparent layer (usually water), the short duration (ns) shock wave pressure of plasma is amplified (up to several GPa) and starts to proliferate into the material [10]. As soon as the induced shock pressure increases higher than the dynamic yield strength of the treated material, a plastic deformation and compressive stress occurs at the surface and subsurface layer of the work piece. [10] One of the major drawbacks of LSPwC is that there is a high possibility of generating a residual tensile stress on the top of the specimen surface. This phenomenon happens due to elevated thermal effect, the surface softening and re-solidification. This phenomenon occurs at the specimen surface or few microns below it due to laser material interaction [11]. Therefore, the magnitude of compressive residual stress generated is affected. Hence, to eradicate these problems low energy laser can be considered to be a right solution by tuning the experimental parameters [12].

2. EXPERIMENTAL PROCEDURES AND METHODS

2.1. Material and specimen preparation

The Monel K-400 sheet was purchased commercially with a thickness of 30 mm. The chemical composition of Monel K-400 is given in table 1. A specimen of measurements 4 cm × 2 cm × 2 mm was set up by cutting a 30 mm thick Monel K-400 sheet by electric discharge machining (EDM) wire cutting machine. The mechanical properties of the base material are displayed in table 2. The specimens were polished with emery sheets with grinding range from 100 - 2000 and were profoundly cleaned to a mirror finish. This was done before the specimen was treated with LSP without coating.

2.2. Laser shock peening without coating (LSPwC)

A Q-switched Nd:YAG laser operating at the fundamental wavelength of 1064 nm was used for LSPwC. There is no sacrificial coating was used hence the name without coating is added to LSP. The LSPwC experiment was performed at room temperature (25° C) condition [11]. This was delivered to the material surface with the help of a dichromatic mirror and a plano convex

TABLE 1
Chemical composition of Monel K-400.

Ni (wt%)	C (wt %)	Mn (wt%)	Fe (wt%)	S (wt%)	Si (wt%)	Cu (wt%)
63.0	0.3	2.0	2.5	0.024	0.5	28.0-34.0

TABLE 2
Mechanical properties of base material (Monel K-400).

Material	Tensile strength (MPa)	Yield strength (MPa)	Modulus of Elasticity (GPa)	Poisson's ratio
Monel K-400	517-620	172-345	179	0.32

lens of focal length 300 mm [8]. The dichromatic mirror was kept at an angle of 45 ° and after that the plano convex lens was placed as shown in fig.1. The lens is protected from the water spilling during the time of peening by an electric drier which is placed near the lens. The specimen was placed on a specimen holder stage which was placed on a computer controlled X-Y translation stage (SVP lasers, India). A short program was written to control the movement of this X-Y translation stage. A thin jet of tap water was used as a containment layer. The thickness of the containment layer was maintained to be 1 to 2 mm throughout the experiment [11]. Another use of the water jet was to continuously remove the ablated material from the specimen surface so as to keep the surface clean while subjecting to LSP. The LSPwC parameters are given in table 3. The laser pulse density *Np* of the laser can be controlled by controlling the velocity of the transitional stage. The pulse density was kept constant in this experiment [13].

If we assume V_X to be the velocity of the specimen in the x-axis and the pitch in the y-axis as Y_P, then we have,

$$Vx = \sqrt{1} / Np \times F \tag{1}$$

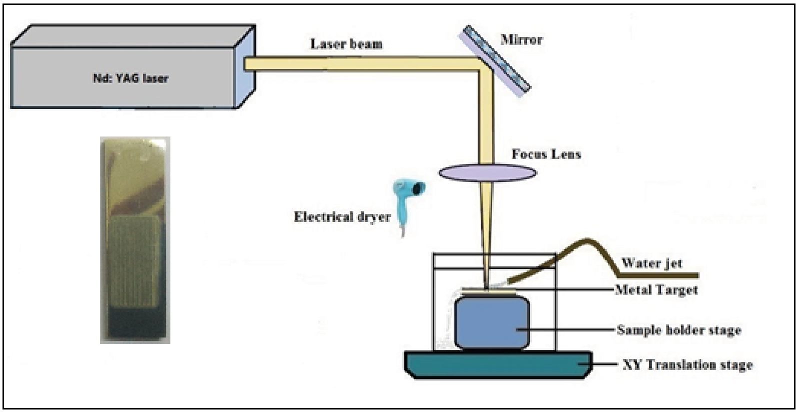

FIGURE 1
Schematic representation of LSP without coating process for Monel K-400 specimen (The specimen image is displayed inside the box) [11].

TABLE 3
Laser shock peening without coating parameters.

Pulse Energy	Pulse duration	Repetition Rate	Power density	Pulse density	Spot diameter
350 mJ	10 ns	10 Hz	6.96 $GWcm^{-2}$	800 pulses cm^{-2}	0.8 mm

$$Yp = \sqrt{1} / Np \tag{2}$$

where, N_P is the laser pulse density and F is the laser pulse repetition rate. [14]

The peak power density G and the coverage C_V can be determined by the above formulae

$$C_V = A_P N_P \tag{3}$$

$$G = E_P / (A_P \tau) \tag{4}$$

where, AP is the beam spot area which is equal to $\pi D^2 / 4$ and τ is the duration of the pulse width in FWHM, which is maintained constant in the present experiment [14].

2.3. Characterization procedure

The specimen is subjected to X-ray diffraction (XRD). Crystallographic analysis was carried out using Scherrer's formula:

$$T = \frac{K\lambda}{\beta \cos\theta} \tag{5}$$

where T is crystallite size in angstroms, λ is the wavelength of X-ray, β is the full width half maxima and θ is the glancing angle [15].

The depth wise compressive stress estimations are taken as indicated by the X-beam diffraction $\sin^2 \Psi$ technique. The X-ray beam of 4 mm^2 at the diffractive edge of 44° is measured by Xpert Pro framework (PANalytical, Netherlands) at a working voltage of 45 kV and current of 40 mA utilizing Cu $_{K\alpha}$-radiation with PRS X-beam detector [11]. The electrolyte polishing progressive layer removal procedure is received for depth examination of compressive residual stress. It is preceded by applying 80% methanol and 20% perchloric acid solution and by controlling the voltage (18V) with steady electro polishing time duration. According to ASTM: E384 standard, the transverse cross-sectional specimens are utilized to quantify Vickers micro hardness [14] estimations with a steady load of (50 gf) was applied for 10 sec duration.

3. RESULTS AND DISCUSSIONS

3.1. X-ray diffraction (XRD) analysis

The existence of significant peaks at 44° of 2θ edge shows the presence of retained austenite in both the peened and unpeened specimens [15]. There is shift in the peak in the treated specimen, showing that the LSPwC treatment brings about the induced lattice strain. Another reason for the shift in the peak is due to the disorientation of the crystalline structure. This is due to the intense shock wave produced by the LSPwC process. From the detailed review of XRD we can get to know that the crystallite size has been reduced altogether after the LSPwC treatment, thus showing grain refinement. From figure (b) we can see that after the laser peening that the intensity of the peak of the treated specimen is more than that of unpeened specimen. This is a direct result of high dislocation density that is accomplished because of LSPwC. It also tells us that there is residual stress is available in the specimen. Fig. 2, 3 and 4 show the X-ray Diffraction graphs.

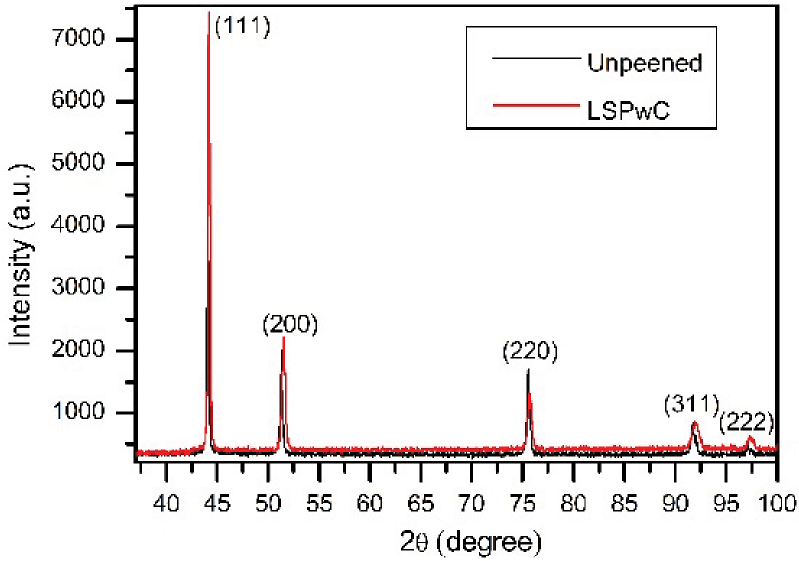

FIGURE 2
Indexed XRD plot diffraction graph of model K-400.

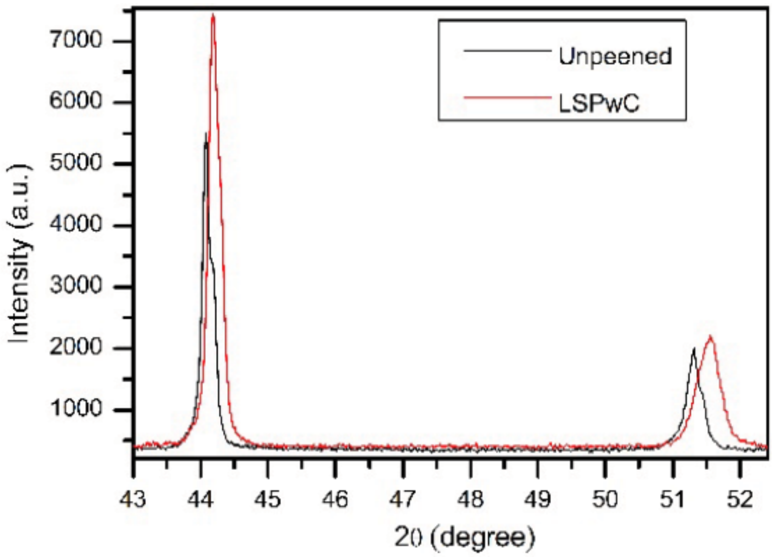

FIGURE 3
Magnified image of XRD peaks at angles 44 and 51°.

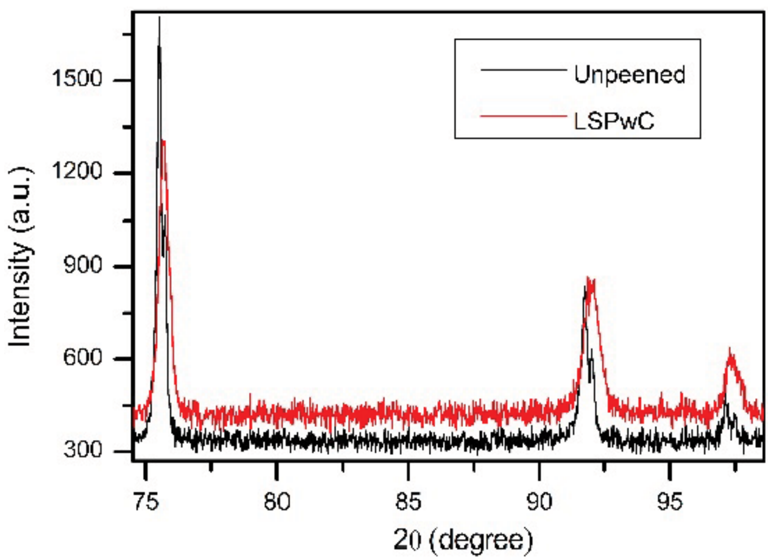

FIGURE 4
Magnified image of XRD peaks at angles 76, 93 and 97 °.

3.2. Atomic force microscope (AFM) analysis

The topographical examination of the specimen which was treated with LSPwC was done utilizing ATOMIC FORCE MICROSCOPE (AFM). The test was performed on an area of 2 μm × 2 μm and sampling length was set as 0.5 mm

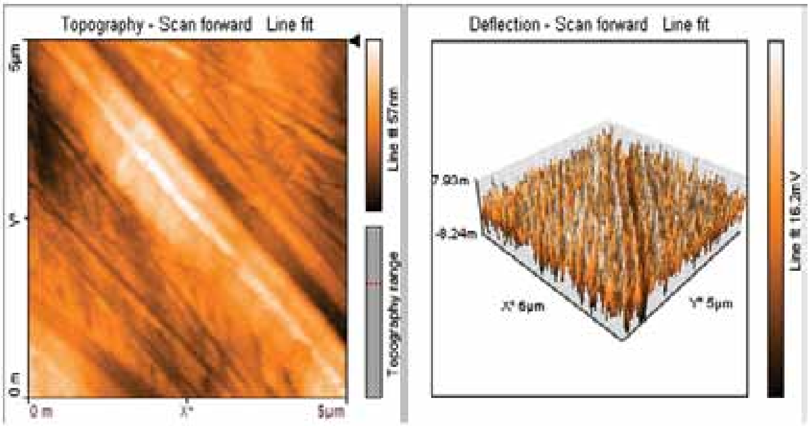

FIGURE 5
Atomic force microscopy for un-peened Monel K-400 specimen.

for the estimations. Owning to disintegration of the surface quality most of the component breakdown begins at the surface. The surface stability of the treated specimen and the untreated specimen was assessed as surface roughness and surface topography [14]. The surface topography of the specimen surfaces are shown in the figure (Fig.5 and 6). From the figure it can be observed that after LSPwC, the valleys are more in LSPwC specimen. So, the nominal amount of surface roughness increment in the LSPwC specimen also supports for the corrosion resistance. The laser shot indentation is the main purpose behind the suppression of peak to valley. Thus from AFM surface topography [11] it can

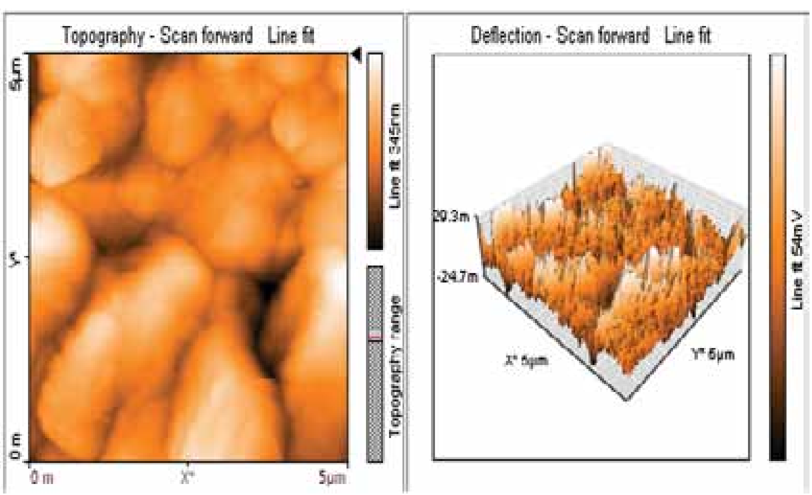

FIGURE 5
Atomic force microscopy for peened Monel K-400 specimen

be seen that the laser peened specimen surface shows more surface roughness than unpeened specimen surface. LSPwC creates nominal increment in the surface roughness of the material and this nominal increment supports the corrosion resistance of the specimen.

3.3. Residual stress analysis

The Residual stress calculation of the peened and unpeened specimen was done by X-ray diffraction $\sin^2\psi$ technique [14], where ψ is the point between the normal to the surface and the normal to the diffraction plane. The residual stress was measured in the sigma-x direction [16]. The initial value of the residual stress is because of the manufacturing procedure. The values of residual stress for unpeened specimen were 13.7 and 31.4 MPa at the surface and depth of 50 microns respectively. The values of residual stress for peened specimen were measured to be -119.9 and -142.7 MPa at surface and at a depth of 50 microns respectively. It can be thus seen that the compressive residual stress was induced in the sample after the LSP process. Laser peened surface demonstrated higher compressive residual stress contrasted with that of the unpeened surface.

3.4. Microhardness analysis

The microhardness was measured using Vickers Hardness Test with varying depths. The normal hardness of the untreated specimens were calculated till a depth of 500 microns. Its value was 144.5 HV. Normal hardness of LSPwC specimen was observed to be risen and calculated to be 150.7 HV. At a profundity of 100 microns in the peened sample the value of hardness attained a maximum value of 156 HV at that point bit by bit began diminishing with increasing profundity, till it indicated comparable hardness values as the untreated specimen at 700 microns profundity. This outcome can be explained due the damping of the intensity of the shock wave with depth distance in the material. This is due to the strain hardening effect of LSPwC. The precipitates which are dispersed at the sub-grain boundaries and also inside the

TABLE 4
Residual stress measurement parameters.

	CuKα
X ray tube Voltage	20KV
X ray tube Current	5mA
Diffractive plate	222
Diffraction angle 2θ	76°
X ray irradiated area	2 mm
X ray detector	PSSD

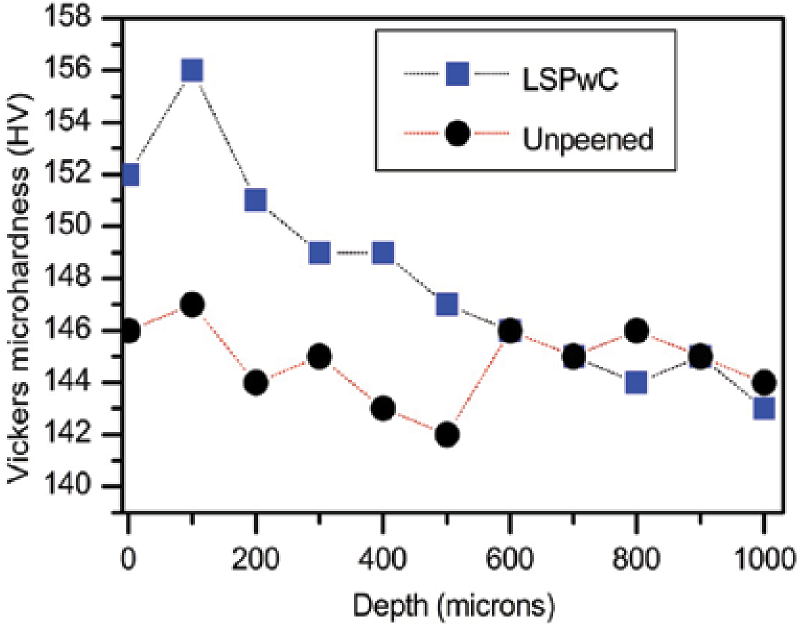

FIGURE 7
The Vickers microhardness profile for unpeened and LSPwC Monel K-400 specimens.

grains obstruct the movement of dislocations giving rise to higher strength in a material.

4. CONCLUSIONS

Laser Shock Peening without Coating studies on Monel K-400 showed an improvement in the surface stress values. The micro hardness test confirmed that the LSPwC process resulted in work hardening as well as the increase in the depth of hardened layer. Increase in the surface roughness was reported after the laser peening process the surface roughness analysis reported an increase in the surface roughness after laser peening thus indicating an increase in the corrosion resistance of the material. Comparative studies of peened and unpeened specimens indicate grain refinement has taken place in the peened specimen which is supported by (XRD) and (AFM) results. More confirmation study is required to identify the improvement in fatigue and wear resistance. Low energy Nd:YAG laser is feasible to perform laser shock peening (LSP). When using low energy laser, peening without sacrificial coating is more beneficial to induce higher magnitude compressive stress. Shot peening produces excess amount of surface roughness. LSP produces nominal amount of surface roughness which will support for the corrosion resistance of Monel K-400.

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