Impact of Vibratory Peening on the Surface Integrity of Cemented Steel E16NCD13

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Abstract

Vibratory peening is an alternative surface modification procedure that combines the shot peening and the vibratory finishing processes together. The process produces compressive residual stresses comparable to those obtained by shot peening, but with better surface finish. The process could enhance the fatigue life of the treated part and improve the industrial productivity by combining the two steps into one single operation. This study aims at determining the surface integrity properties of E16NCD13 steel after vibratory peening. Surface roughness, compressive residual stresses (CRS) and microhardness were evaluated after vibratory peening at different Almen intensities and compared with shot peening. It was found that vibratory peening decreased the surface roughness and was better than shot peening for specific Almen intensities. Moreover, vibratory peening induced deeper CRS and increased the micro-hardness of the cemented steel.

Keywords: Vibratory peening, Almen intensity, Surface roughness, Cemented steel, Residual Stress

Introduction

Vibratory peening is a recent development that combines the processes of shot peening and vibratory finishing into one step [1]. The surface roughness increases after shot peening, which raises the stress concentrations at the surface causing the fatigue life to decrease [2]. Vibratory finishing as an additional process is applied after shot peening to reduce the stress concentrations and improve the surface conditions [3]. Vibratory peening induces compressive residual stresses similar to those of shot peening but with a better surface finish. Consequently, the fatigue life could improve after vibratory peening, and the process could increase the industrial productivity since it combines two individual processes into one single operation. The key parameters of vibratory peening are processing time, vibration amplitude, media type, media mass, part position and orientation of the tub.

E16NCD13 is a case hardened cemented low alloy steel which is used widely in aerospace components like gears and gearboxes [1]. These components experience fatigue under contact loading and in the form of load reversals, for which the surfaces require treatments to improve their service lives. Case hardening is usually applied on E16NCD13, which increases the hardness of the surface around 700 HV [4]. Studies revealed that vibratory peening has the potential to alter the surface properties of E16NCD13 steel. Surface roughness was found to decrease with vibratory peening time at constant Almen intensity [1]. The maximum residual stress increased by 345% and the depth of CRS by 135%, when the Almen intensity was increased from 0.12 mmA to 0.25 mmA [1]. It was found that for higher Almen intensities, higher processing times and higher frequencies led to deeper and larger CRS in E16NCD13 steel after vibratory peening [1]. Hardness was also found to increase after vibratory peening, which is mainly affected by the reduction of media mass [1]. In other alloys, when compared with shot peening, the surface roughness after vibratory peening was lower, for similar Almen intensities [5,6]. Shot peening produces higher CRS for similar Almen intensities but higher depth of penetration is achieved by vibratory peening [5,6]. However, the current literature lacks any report on systematic investigation of the surface properties of E16NCD13 steel after shot and vibratory peening. Moreover, the influence of the vibratory peening parameters on the Almen intensity and surface integrity also needs emphasis.

The current work tries to fill up this gap. The objectives are primarily (a) calibrating the process parameters of a vibratory peening system using a DOE method and understand the influence of these parameters on the Almen intensity, and (b) compare the surface properties of E16NCD13 steel after vibratory and shot peening for different Almen intensities, where the vibratory peening is performed with process parameters found suitable from objective (a). This paper mainly discusses the comparison of surface properties after shot and vibratory peening of E16NCD13 steel for different Almen intensities, i.e., the objective (b).

Experimental Methods

The E16NCD13 steel selected in this study was obtained after case hardening with a case depth of 1.1 mm. The material is manufactured according to the ASTM 4911N standard with a chemical composition according to Table 1. Specimens of 60 x 19 x 8 mm^3 were cut from 100 mm round bars. The hardness of the steel at the surface ranged between 750 and 780 HV whereas the bulk hardness varied between 340 and 430 HV. The average surface roughness R_a of the E16NCD13 steel in the as-received condition was 0.2 μm in the longitudinal direction and 0.25 μm in the transverse direction.

Table 1: Chemical composition of the selected E16NCD13 cemented steel [7]

Element		Fe	C	Mn	Si	Cr	Ni	Cu	Mo	P	S
Wt%	Min.	Bal	0.13	0.30	0.15	0.80	3.00	-	0.20	-	-
	Max.	Bal	0.17	0.60	0.40	1.10	3.50	0.35	0.30	0.015	0.010

The vibratory peening machine was designed and manufactured by Vibra Finish in collaboration with Polytechnique Montreal and Safran Tech, France. The treated specimens were attached with a holder inserted into a tank resting on air bags and filled with carbon steel media (3 mm diameter). Two shafts with eccentric weights rotating in opposite directions on each side of the tub were used to produce oscillations in the vertical direction. The controlling parameters of vibratory peening were found out to be the eccentric weights on the shafts (X_Ecc), the media mass inside the tank (X_Mass), the rotating shaft frequency (X_Freq), the airbags pressure (X_Press), the media height above the part (X_Height), the horizontal part position (X_Pos) and the lubricant flow rate (X_Lub). The vibratory peening process was calibrated using a DOE method in which the effect of parameters on the Almen intensity was analyzed in detail. From these analyses, the process parameters selected for the vibratory peening of E16NCD13 steel at Almen intensities of 0.1, 0.15 and 0.2 mmA are: X_Freq = [20, 22.5, 25, 27.5 and 30 Hz], X_Height = 10 and 25 cm, X_Mass = 500 kg, X_Ecc = 24 kg/shaft, X_Press = 2.8 bars, X_Pos = centre and X_Lub = 20 rpm.

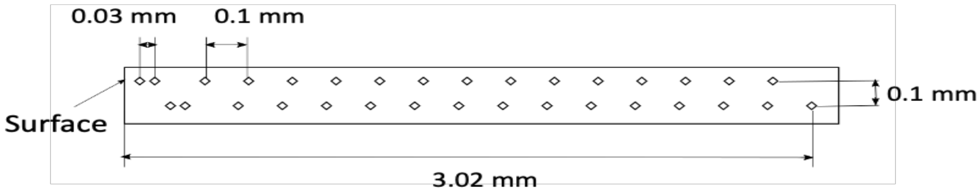

Figure 1: Schematic of the microhardness profile measurement points undertaken on the peened specimens for evaluation of the microhardness profiles.

2D surface roughness measurements were performed after peening using a Mitutoyo SV-C4000 series profilometer (resolution of 0.05 µm). The roughness parameters were calculated in accordance to ISO 4287 standard. The measurements were conducted at multiple locations on a peened surface in both longitudinal and transverse directions.

The residual stress profiles measurements were carried out using X-ray diffraction method with a goniometer Stresstech Xstress 3000 G2R, 7257/7258 according to ASTM E915-16.

Microhardness profiles were measured after peening with a MVK-H0 hardness tester using a 300 gf according to ASTM E384 standard [8]. In each case the profiles were evaluated using 32 indentations across the surface in a pattern shown in Figure 1. Two measurement lines spaced 0.1 mm apart with 16 indentations in each line were formed to measure the micro-hardness profiles.

Experimental Results

Surface roughness measured after vibratory peening showed a decrease in the surface roughness after peening at all intensities, where the decrease was more pronounced in the longitudinal direction, when compared to the transverse direction. This is because the grinding marks were along the longitudinal direction for which the surface roughness values are higher in transverse direction. Table 2 lists the average surface roughness R_a (µm) obtained for the E16NCD13 steel after vibratory peening at different Almen intensities and direction of measurement, when peened for two time periods, T_{sat} and $2T_{sat}$. T_{sat} is the processing time which corresponds to the point between arc height vs processing time where doubling the peening time produces no more than a 10% rise in arc height. Further details can be found in SAE J443 [9]. In each case three measurements were used to calculate the average values along with the standard deviation, as reported in Table 2.

Table 2: Average surface roughness, R_a (µm), of E116NCD13 steel measured for two different specimen directions and saturation time after vibratory peening at various Almen intensities

Almen Intensity (mmA)	Average Surface Roughness, R_a, (µm)					
	Longitudinal			Transverse		
	As-received	T_{sat}	$2T_{sat}$	As-received	T_{sat}	$2T_{sat}$
0.1	0.19 ± 0.03	0.09±0.02	0.08±0.009	0.25 ± 0.05	0.27±0.03	0.28±0.04
0.15		0.105±0.009	0.109±0.02		0.25±0.07	0.22±0.04
0.2		0.13±0.014	0.13±0.011		0.30±0.011	0.19±0.007

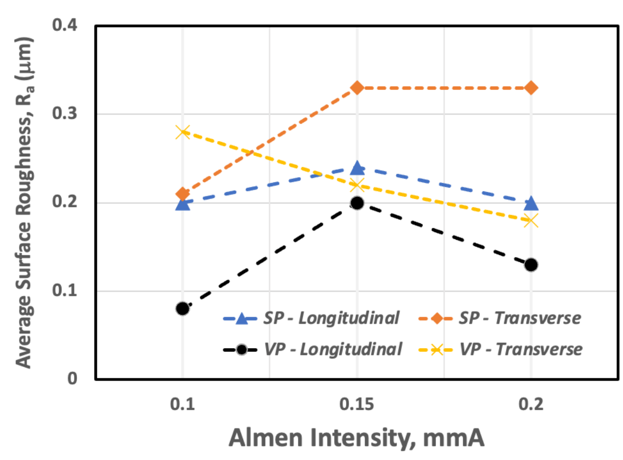

Figure 2: Variation of average surface roughness, Ra (μm), along longitudinal and transverse directions after both shot and vibratory peening at different Almen intensities.

It can be seen that the surface roughness has the tendency to increase with increasing Almen intensity in both directions. In the longitudinal direction, the surface roughness values become stable after T_{sat}, irrespective of the Almen intensity. In the transverse direction, the values decrease after T_{sat}, and the saturation of surface roughness is found to be dependent on the process parameters. When comparing with shot peening, it is observed that the surface roughness was smaller in almost all cases after vibratory peening. Figure 2 shows the average surface roughness R_a (μm) along the longitudinal and transverse directions at various Almen intensities after shot and vibratory peening. For almost all the Almen intensities, the surface roughness is lower for vibratory peening in both the longitudinal and transverse directions. The results reflect the efficacy of vibratory peening in lowering the surface roughness in comparison to shot peening.

Compressive residual stresses were evaluated at the surface up to a certain depth for E16NCD13 steel after vibratory peening at different Almen intensities. Figure 3 shows the variation of CRS with depth from surface at three different Almen intensities. The variation of CRS between Almen intensity 0.1 and 0.15 mmA is marginal, with the CRS slightly higher in the 0.15 mmA Almen intensity. However, the CRS increases substantially at 0.2 mmA Almen intensity, where the maximum CRS is -845 MPa. Interestingly, the depth at which the maximum CRS occurs is also higher in case of 0.2 mmA Almen intensity, when compared to others.

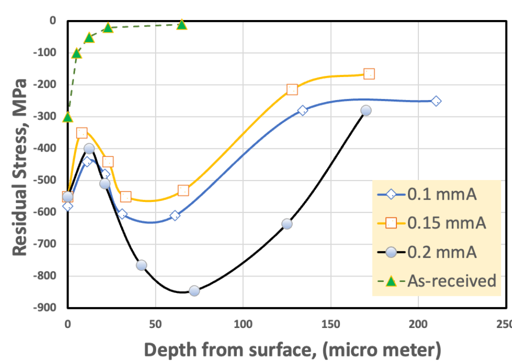

Figure 3: Variation of CRS with depth from surface after vibratory peening at different Almen intensities where the processing time was $2T_{sat}$ and X_Height is 25 cm.

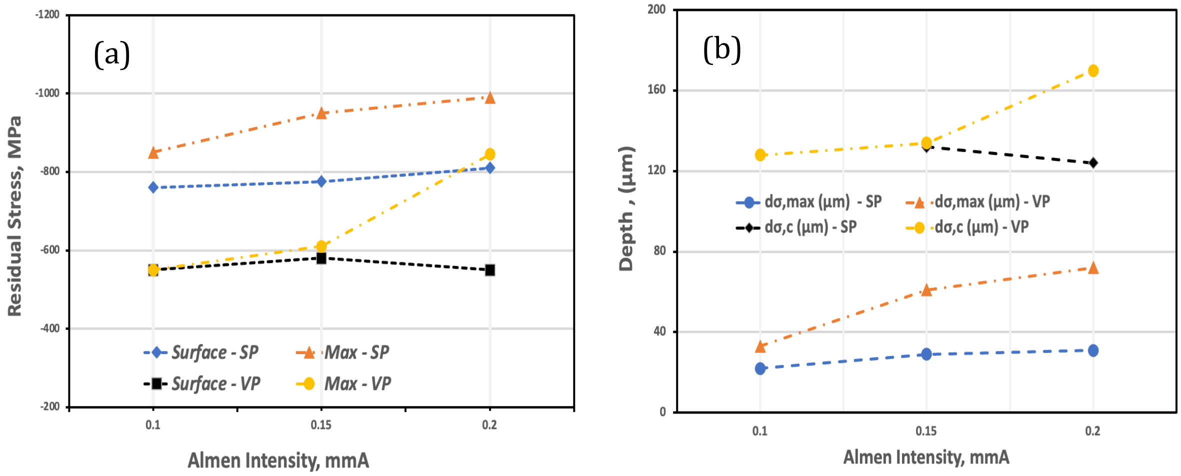

Figure 4: (a) Residual stress values measured at the surface of E16NCD13 steel and the maximum compressive residual stress after shot and vibratory peening at different Almen intensities, and (b) depth of maximum CRS values obtained from CRS distribution after shot and vibratory peening at different Almen intensities.

When comparing with shot peening, it was found that the residual stress at the surface and maximum CRS are always higher after shot peening at all the Almen intensities, as shown in Figure 4(a). However, the depth of the compressive residual stress is always higher for vibratory peening at all intensities, as shown in Figure 4(b). This comparative assessment of the distribution of CRS shows that although shot peening produces higher CRS, which will be effective in retarding the fatigue crack growth, this effect might be more pronounced up to higher depth in vibratory peening.

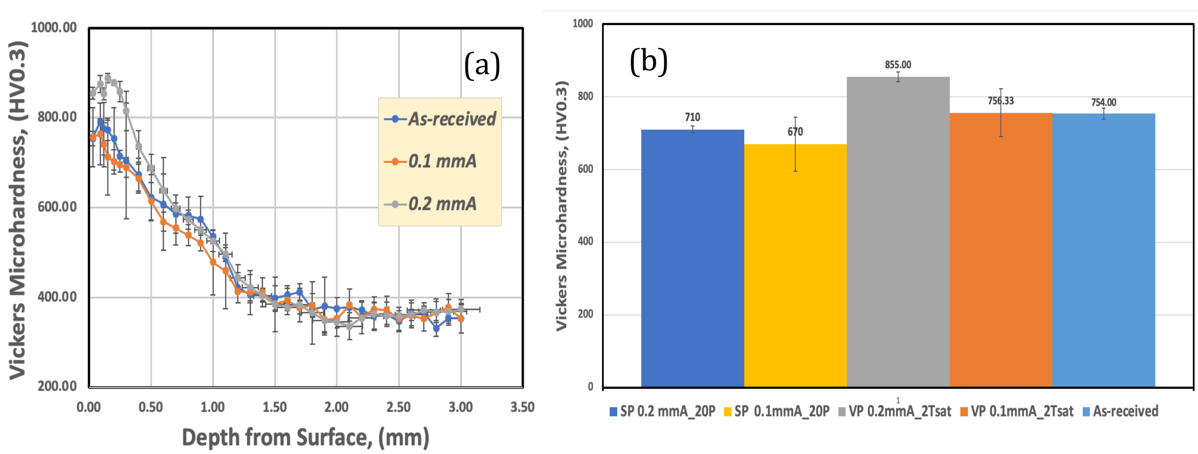

Figure 5: (a) Vickers microhardness profiles from the surface of E16NCD13 steel after vibratory peening at various Almen intensities and (b) average microhardness values at the surface after shot and vibratory peening for two different saturation time for 0.1 and 0.2 mmA Almen intensity.

Microhardness profiles were measured on the cross-section, from the surface of peening, according to Figure 1. The results show that the microhardness at the surface changes marginally from the as-received state when vibratory peened at 0.1 mmA Almen intensity. In fact, the change in hardness was not so pronounced after peening at 0.15 mmA Almen intensity. Figure 5(a) shows the hardness profiles from surface in as-received and after vibratory peened at 0.1 and 0.2 mmA Almen intensity. The increase in hardness is only observed at the surface and a few micrometers (0.6 μm) below the surface for 0.2 mmA Almen intensity. Even after shot peening, the microhardness did not show any significant variation, as shown in Figure 5(b). The maximum increase in microhardness at the surface was only found after vibratory peened at 0.2mmA Almen intensity.

Concluding Remarks

The surface of a EN16NCD13 cemented steel specimen was treated using the vibratory peening method at three different Almen intensities, which are 0.1, 0.15 and 0.2 mmA. The surface properties were evaluated after the peening and the results showed that vibratory peening can produce a better surface finish. The surface roughness was reduced after vibratory peening, although the degree of reduction depended on the direction of measurement and Almen intensity. Moreover, the surface roughness after vibratory peening was always lower than that of shot peening. In terms of residual stress, vibratory peening did produce compressive residual stresses beneath the surface, but the maximum CRS was lower than what is obtained after shot peening. However, through vibratory peening, deeper depth of CRS was achieved. Microhardness, on the other hand, showed negligible change from the as-received state and the maximum increase in microhardness was only observed at the highest Almen intensity of 0.2 mmA. Together with better surface finish and deeper CRS, vibratory peening has the potential to limit crack initiation at the surface and restrict crack growth at the sub-surface layers.

The current work only discussed the results obtained from experiments related to surface integrity. These findings need further experimental validation through observation of microstructure of the peened layers, which is being currently undertaken at Polytechnique Montreal with the technical and financial support of Safran Tech, France.

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