➢ ***ORAL PRESENTATION***

Influence of Shot Peening on Surface Residual Stress and Microstructure Evolutions of R260 Rail Steel

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Abstract

In this study, shot peening (SP) was performed on R260 rail steel. The effects of SP treatment on surface properties such as surface topography, microstructure, residual stress, and microhardness were investigated using optical microscopy, X-ray diffraction, and microhardness measurements. Increasing both the peening intensity and surface coverage effectively produced a gradient structure in the surface layer of R260 rail steel, characterized by high compressive residual stress and significant work hardening. The enhancements in grain refinement, compressive residual stress, and work hardening achieved by increasing surface coverage were more pronounced than those obtained by simply raising the Almen intensity. Under the 24A-1000 shot peening condition, the steel exhibited a residual stress of approximately 1.24 GPa and a surface hardness of roughly 410 $HV_{0.01}$.

Keywords: R260 rail steel, Residual stress, Shot peening.

INTRODUCTION

Increasing demands on rails such as higher speeds, heavier loads, greater traffic density, and mixed traffic lead to heightened damage, primarily through wear (profile loss), plastic deformation, corrugation, and rolling contact fatigue cracking. In contrast, for tramways and light rail systems, wear is the predominant form of damage, largely due to frequent braking and acceleration, sharp curves, high traffic frequency, and fluctuating loads (Solano-Alvarez et al., 2019). In metallic materials, surface integrity is typically improved through grain refinement and the introduction of compressive residual stress in the surface layer (Gerin et al., 2016). When these techniques are effectively applied, they can significantly enhance material performance, including increased resistance to fracture, fatigue, corrosion, wear, and crack propagation (Maleki et al., 2018).

Shot peening (SP) is a well-established and widely used severe plastic deformation technique employed to refine grain size and introduce compressive residual stresses (Maleki and Unal, 2018). The plastic deformation capability of metallic materials depends on the mobility of dislocations and the rate of plastic strain. When dislocation movement is hindered, the material’s strength increases, although this often leads to reduced ductility. Work hardening results from an increase in dislocation density caused by plastic deformation (Unal et al., 2022). In the SP process, the degree of plastic deformation is directly influenced by the total impact energy applied.

In the present study, SP process was applied to R260 rail steel to evaluate its potential for inducing residual stress and grain refinement in the surface layer. The effects of SP process on surface residual stress, microstructure, and microhardness evolution were comprehensively investigated using X-ray diffraction (XRD), light optical microscopy (LOM), and microhardness measurements. Additionally, the as-received R260 rail steel was prepared as a control for comparative analysis.

MATERIALS AND METHODS

In this study, R260 rail steels having the chemical composition of (in wt. %) C: 0.6-0.82, Mn: 0.65-1.25, Cr: 0.15, Si: 0.13-0.60, P: 0.03, S:0.01, Mo:0.02, Fe: balance; were selected. Table 1 demonstrates the mechanical properties of R260 rail steel.

Table 1. Mechanical properties of R260 rail steel.

Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)
880	640	25.7

The as-received R260 rail steels were subjected to SP using an industrial air blast machine (Sigma Shot Peening Company, Istanbul) under different conditions shown in Table 2. The treatments were carried out with S230-grade steel shots (hardness: 40-51 HRC) at surface coverages of 200% and 1000% to ensure complete peening of the steel surfaces. The intensities were determined using an Almen gauge with standard "Almen A" test strips. Shot peening was applied at two different Almen intensities (16A and 24A).

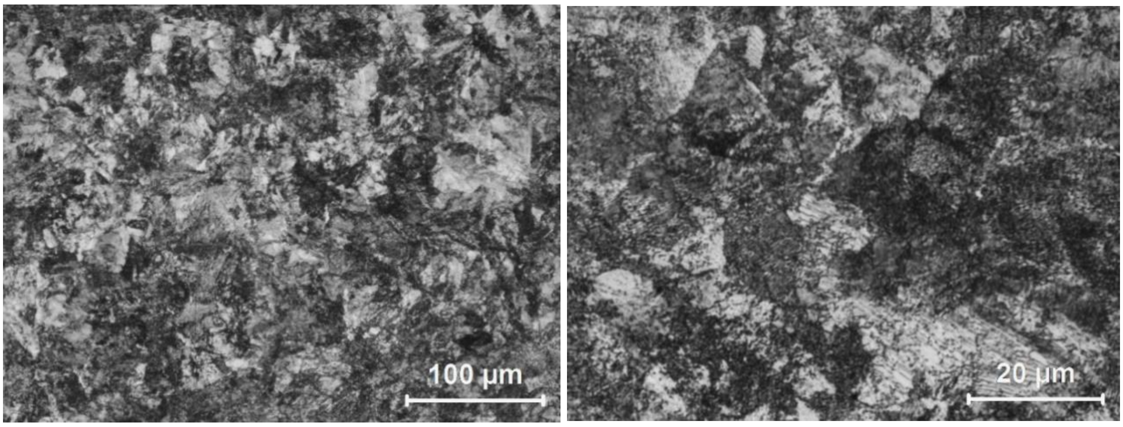
Table 2. SP conditions on R260 rail steel.

Treatment ID	SP Almen Intensity	Grinding Coverage (%)
16A-200	16A	200
24A-200	24A	200
24A-1000	24A	1000

After shot peening treatments, the structural analysis of the cross-section of the shot peened steels was performed using a light optical microscope (LOM, Nikon Eclipse LV150). Etching process was carried out by immersing the specimens in 2 % nital etchant for 15 s. The phases of the untreated and shot peened steels were identified using an X-ray diffractometer (XRD-Panalytical Empyrean) with CuK$_\alpha$ radiation, scanning in the 2θ° range from 30° to 110°, at an angle step of 0.020° and a scanning speed of 1°/min. Also, the residual stress measurements were performed by the fixed incident multiplane technique (FIM) method. The details about this method can be found elsewhere (Sarioglu, 2006). The roughness parameters (R_a and R_q) were measured with a Mitutoyo contact profilometer (SJ-400 model), based on ISO 4287 standard. Microhardness was measured with the Shimadzu HVM tester with a 10 g load at 10 μm intervals up to 110 μm from the surface in the polished cross section.

RESULTS and DISCUSSION

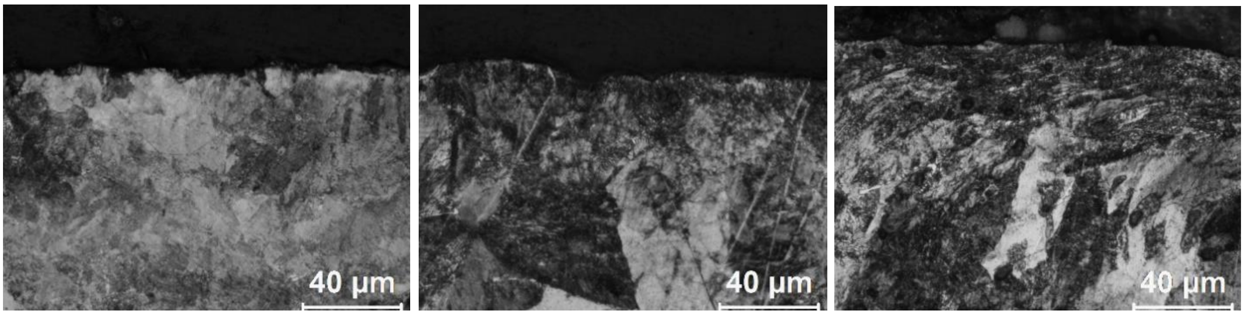
As expected, it was seen that the R260 rail steel showed pearlite colonies characterized by alternating lamellae of cementite and ferrite, as shown in Fig. 1.



(a) (b)

Figure 1. (a) Low and (b) high magnification LOM micrographs of the R260 rail steel.

Figure 2 shows the cross-sectional microstructures in the near surface layer after SP operations. It is evident that the conventional peening parameters (16A-200 and 24A-200) caused a moderate level of plastic deformation in the surface layer, accompanied by microstructural refinement (Fig. 2 a and b). When SP was applied at a constant Almen intensity of 24A with increasing surface coverage from 200% to 1000%, the surface grains were compressed, resulting in the formation of a distinct structure near the surface (Fig. 2 c). It was observed that the pearlite grains were oriented significantly, and their size decreased as well in the layer affected by deformation. In this region, the grains became significantly finer, their boundaries blurred, and they merged into a uniform, homogeneous layer. The depth of this fine-grained layer varied depending on both the Almen intensity and surface coverage. As these parameters increased, the deformed layer thickened, and its thickness distribution across the surface became more uniform (Unal et al., 2022).



(a) (b) (c)

Figure 2. LOM observations of shot-peened steels in the (a) 16A-200, (b) 24A-200 and (c) 24A-1000 conditions.

Figure 3 shows the XRD patterns from the surface layer of the untreated and shot peened steels. Each steel exhibited characteristic iron-based peaks (α-Fe). Compared to the untreated steel, the α-Fe peak intensity decreased and the peaks broadened and shifted toward lower angles in the treated steels as the Almen intensity and surface coverage increased. Furthermore, the α-Fe peaks of the shot-peened steels were broader and appeared at lower angles, indicating a grain refinement, higher lattice distortions, and compressive residual stresses due to the dislocation density compared to untreated steel. Using Bragg's law ($n\lambda=2d\sin\theta$), where d is the distance between planes, θ is the diffraction angle, n is a positive integer, and λ is the XRD beam's wavelength, we can figure out the lattice parameters (a) of the untreated and shot peened steels by using the main α-Fe peak (i.e., one that falls in the (110) diffraction plane) as a guide. Calculated average values for the untreated and shot-peened steels in the 16A-200, 24A-200 and 24A-1000 conditions to be 0.287227 nm, 0.287307 nm, 0.287395 nm, and 0.288345 nm, respectively. Thus, compared to the untreated R260 rail steel, the shot-peened steels in the 16A-200, 24A-200 and 24A-1000 conditions exhibited a relative extension in the lattice parameter ($\Delta a/a$) of approximately 0.028%, 0.058%, and 0.39%, respectively. This finding indicated the development of a larger compressive residual stress on the surface of the shot-peened steels, as modelled by Leskovsek et al. (Leskovšek et al., 2008).

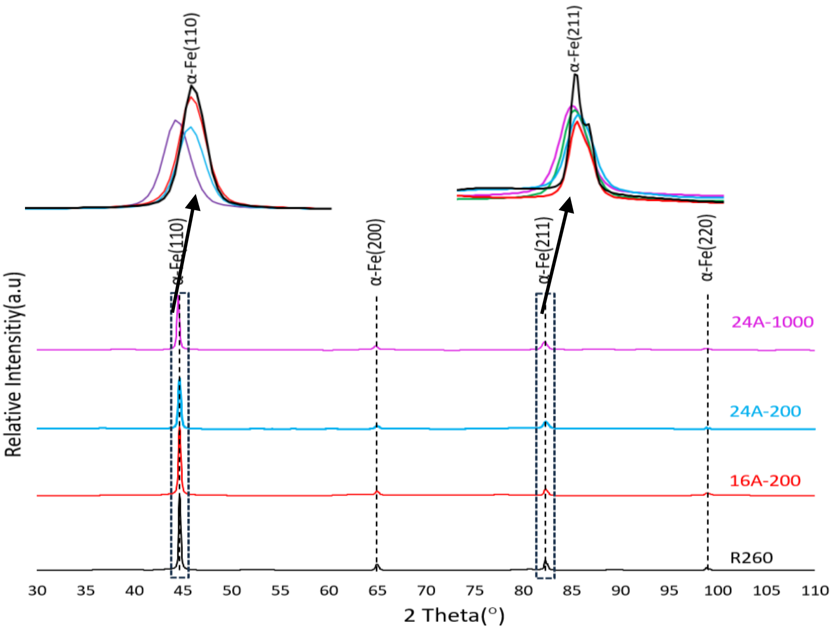


Figure 3. XRD patterns of the untreated and shot peened steels.

Figure 4 shows the surface roughness plot versus different SP conditions. The treatment with the lowest roughness value (R_a) was as received (0.12 µm) one. On the contrary, the treatments with the highest value were shot-peened steels in the 16A-200 and 24A-200 conditions. Hence, SP process raised the surface roughness, and in this study the intensity of the treatment caused the roughness increase regardless of the operation. The surface roughness generally increases by the plastic deformation capability; however, the increase does not only change depending on the Almen intensity. Increasing the surface coverage from 200% to 1000% at a constant Almen intensity of 24A played a role in reducing surface roughness.

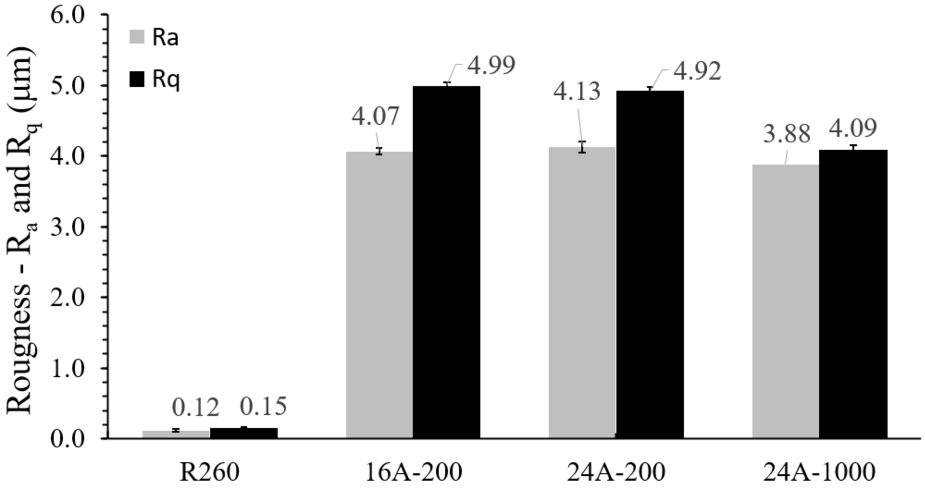


Figure 4. Surface roughness measurements of the the untreated and shot peened steels.

Figure 5 presents the variation in compressive residual stress values of untreated and shot-peened steels, calculated using the FIM method. The untreated steel exhibited no compressive residual stress, with stress levels remaining close to zero (Fig. 5). However, minor stress variations were detected, likely resulting from prior machining and the casting and/or forming processes. In a general aspect, the compressive residual stress increases by the increase of Almen intensity and surface coverage. Compared to the untreated steel, the compressive residual stress values of shot-peened steels in the 16A-200, 24A-200 and 24A-1000 conditions increased by approximately 180%, 190%, and 1027%, respectively.

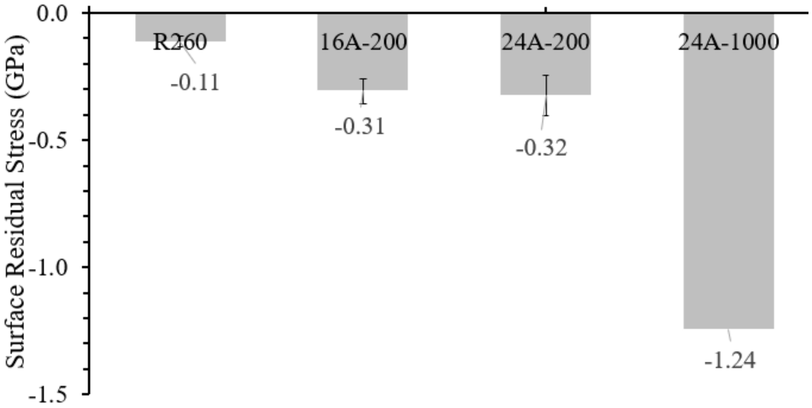


Figure 5. The residual stress state of the untreated and shot peened steels.

Figure 6 illustrates the microhardness values as a function of depth, allowing the estimation of the work-hardened layer thickness. The untreated R260 rail steel maintains a consistent base microhardness of around 300 $HV_{0.01}$. In contrast, shot-peened steels exhibit a decrease in hardness as depth increases. Specifically, the surface hardness values of shot-peened steels in the 16A-200 and 24A-200 conditions are approximately 330 $HV_{0.01}$ and 349 $HV_{0.01}$, respectively, and they return to the base value at depths of around 45 µm and 80 µm. Clearly, surface work hardening is much more evident in the Almen intensity of 24A with surface coverage of 1000%, the surface microhardness is substantially improved to 407 $HV_{0.01}$, which is ~1.35 times higher than that of the base material, and the work-hardened zone reaches nearly 110 µm thick. These findings indicate that increasing surface coverage is more effective than raising Almen intensity in enhancing cold work.

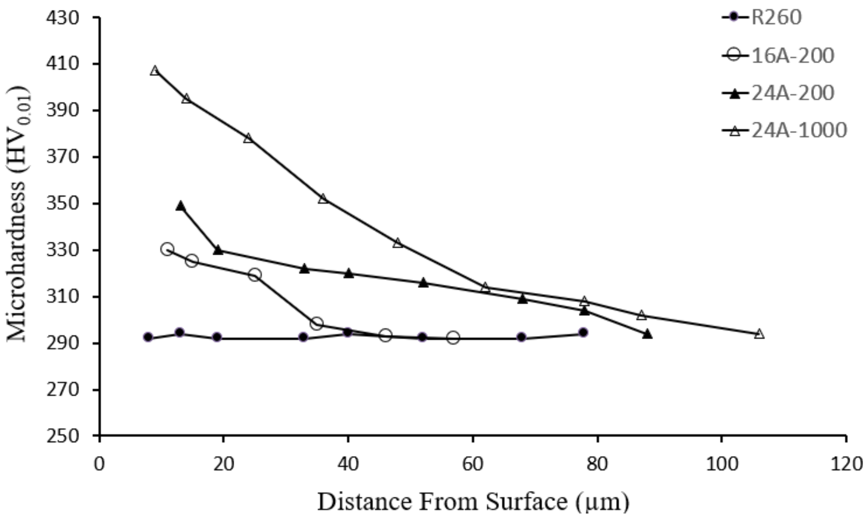


Figure 6. The microhardness change of all treated steels versus depth.

CONCLUSION

In the current work, R260 rail steel was processed by shot peening with different peening parameters. The results of this study can be summarized as follows:

-Enhancing the peening intensity along with applying a high surface coverage successfully produced a gradient structure characterized by high compressive residual stress and pronounced work hardening in the surface layer of R260 rail steel.

-The improvements in grain refinement, compressive stress, and work hardening achieved through increased surface coverage were more significant than those resulting from a higher Almen intensity. For the 24A-1000 shot-peening condition, the residual stress and surface hardness of the steel were approximately 1.24 GPa and 407 $HV_{0.01}$, respectively.

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