Influence of Shot Peening on Surface Characteristics of Case Hardened SAE9310 Gear Material

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Abstract. The shot peening is the cold working process by which the compressive residual stresses are induced in the component, and that increases surface hardness, which can be helpful to avoid the fatigue failure of the component. Shot peening process is using to improve the fatigue life of the automobile and aerospace components. Effectiveness of the shot peening in surface characteristics can be measured by the Almen Intensity, Surface hardness and Surface roughness. The impact of shot peening on case-hardened differential bevel gear is defined in this study. In the shot peening process, the surface of the gear rammed by the small hardened cut wire shots with high velocity and overlapping indentations are created on the gear surface. Hence, the characteristics of surface of the gear can be greatly improved by shot peening. For bevel gears, bending fatigue crack is the major failure mode. This study is discussed to enhance the mechanical and surface properties of SAE9310 bevel gear by using the shot peening process. The optimization of shot peening process is done by including multi-performance characteristics i.e. Intensity, Surface hardness and surface roughness of the bevel gear. The analysis includes air pressure, nozzle distance, shot flow rate, exposure time as process parameters. The main objective of this study to decide the optimized shot peening process parameters for required performance characteristics and most influencing factors on surface layer characteristics. The experiments have been conducted using Taguchi’s L9 orthogonal array design techniques.

1. Introduction
The Shot peening is one of the fatigue life improvement process, residual stresses are induced on the surface of the components by using hardened spherical shots, the shots is also called as peening media [1]. The fatigue life is important feature for automobile and aeronautical parts, introducing the residual stresses on the surface layerof the components by the shot peening process [1]. Automobile components and structural parts are regularly subjected to alternate loads, which made them chance to fatigue failures [2]. As known, almost all the fatigue failures form at surface due to variety of surface stresses concentration due to cyclic loads, including grain boundaries, machining tool marks, surface breaking inclusions and impurities [2]. Fatigue performance is depend on the following main factors: 1. Metallurgical, 2. Surface characteristics 3. Residual compressive stresses [2]. Peening is done
at room temperature so, it is called a cold working process and used to improve the mechanical properties such as fatigue, stress corrosion cracking, and so on. The toughness of the gear can be improved by shot peening process also tensile strength of the components can be increased by peening. Surface cracks and microscopic imperfections are eliminated by shot peening process. So the peening process are recommended for repeated and complex load application parts like springs, axles, gears, aircraft alighting gears, structural parts and gear shafts [3]. In the shot peening process, hardened or soft peening media collided on the surface of the components and developed the compressive residual stresses on the surface layer [4]. Indentations on the surface are created due to radial stretching and plastic flowed by high velocity peening media [5]. Shot peened components are withstands the tensile stresses till overcome the compressive stresses. So the tensile strength of the peened component is improved when compared to original non-peened parts [6]. Another important effect of shot peening is removal of stress concentration points by creating the blends on the surface imperfections. Removal of stress raisers used to improve the fatigue life of the parts. Peening media can be classified as metallic and non-metallic media. Steel cut wire, cast iron, SS spherical shots are the example for metallic media. Glass beads, ceramic balls are the examples for non-metallic media [2]. Glass beads are used in the shot peening on thin sectional components.

The persuaded depth of residual compressive stresses layer is depend on the shot peening intensity [7]. Peening intensity is the important parameter of shot peening process, Almen intensity is well-defined as the measurement of kinetic energy of the shot peening media [8]. Peening intensity depends on the following process variables likeshot material, shot size, hardness of the shot, shot velocity, effect angle, shot coverage and flow rate of the shot [8]. Shot peening process can be used on harden and the soften components. Selection of peening media is playing vital role to peen harden and soften components. Shape of the peening media also important for uniform peening, media should be freed from sharp corners and irregular shapes. Ideally recommended the round shots with uniform size and hardness for a better performance [8]. Shot peening is used in many industrial sectors like Medical, Automobile, Aerospace, Marine, Railway Civil constructions, etc. [9].

1.1 Literature Survey
E. Nordin1 and B. Alfredsson [1] investigated the shot peening effects on “Case Hardened SS2506 steel”. The conclusion was the highest residual compressive stresses achieved on the test specimen at maximum Almen intensity. Also found significant effects on surface topography and removal of grinding marks on the peened surface. Jose Solis Romero [2] studied and found the shot peening process created the plastic deformation on the surface layer and coverage, impact angle, feature of shots were played major role on the surface roughness of Al alloys. Impact angle and shot parameters strongly influenced on compressive stress distributions. Hetram, Lakhwinder Singh and Hari Om [8] investigated the optimisation of shot peening process by mathematical model using the FASTRAN and ANOVA software. Nordin E, Alfredsson B [10] measured the peening media velocity by indent size comparison and concluded the higher size media given the best intensity results. Prevey PS and Cammett JT [11] studied the effects of peening coverage on fatigue. Residual stress and cold work in an alloy “Ni-Cr-Mo steel” and observed shot peening performed to reduce coverage with bigger shots, provided reduction in cold work and profounder compression without any loss in fatigue performance. Kirk D [12] investigated the intensity curves of shot peening and observed Almen strip measurements were curiously effective to generate the indentation curvature and shot peening intensity curve used to create the “Saturation intensity”.

1.2 Objectives
The objective of this study to get the effective results by the optimization of shot peening process parameters and find out the greatest influencing factors on respective results. Design of experiments have been done using Taguchi L9 orthogonal array. The selected process parameters were air pressure,
nozzle distance, shot flow rate and exposure time. The process parameters to be optimized based on the following results Intensity, Surface hardness and surface roughness.

2. Experimental set-up

2.1 Test samples
Test samples used in this experiment, as shown in fig. 1. They are straight differential bevel gears as per below specifications. The bevel gears are widely using in the automobile differential applications. Bending fatigue failure starts from root radius of the bevel gear. So experimental aim to induce the compressive stresses on the root area.

No. of teeth \( z = 11 \)
Module \( m = 6.5678 \)
Pressure angle \( \alpha = 26.0 \) degree.
Outer diameter \( OD = 76\)mm.
The total height \( H = 30\)mm.

![Figure1. Sample bevel gear.](image)

![Figure2. Bevel gear locating on Shot peening fixture.](image)

2.2 Test sample materials
Gear samples were manufactured from SAE9310 low carbon Ni-Cr-Mo case-hardening alloy steel. SAE9310 alloy steel having good toughness, hardenability, core hardness and fatigue strength properties. This alloy steel contains 3.5% nickel and 1.4% chromium so, it’s having very good toughness and strength properties. SAE9310 using in bigger cross-sectional components like crankshafts, different type of gears, and heavy-duty shafts in aircraft, and automobile segments. The detailed chemical composition were attached in the below table 1. The actual measurement results were mentioned in bolted letters.

|                | C   | Si  | Mn   | S   | P   | Ni  | Cr  | Mo  | Cu  | Al  | Ti  |
|----------------|-----|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|
| Min.           | 0.08| 0.15| 0.45 | -   | -   | 3.00| 1.00| 0.08| -   | 0.02| -   |
| Max.           | 0.13| 0.35| 0.65 | 0.02| 0.025| 3.50| 1.40| 0.15| 0.35| 0.05| 0.01|
| Actual         | 0.10| 0.26| 0.64 | 0.004| 0.014| 3.18| 1.12| 0.095| 0.13| 0.028| 0.002|
2.3 Sample preparation
Samples were prepared from SAE9310 peeled and ground steel bar. The bar cut into small billets as per input weight requirement and done the hot forging between 1060°C to 1120°C. Then hot forge gear blanks were normalized for grain uniformity and done the Orbital cold forming to achieve the Gear topography and pitch errors. Cold formed samples moved to CNC machining for removal of unwanted materials and met the gear print requirement. Machined parts sent to Heat treatment process.

2.4 Heat treatment process
Gas carburizing is the heat treatment process to increase the hardness on the surface of the components. In the carburizing process, carbon induced on the surface of the gears up to particular case depth by using controlled Carbon Potential (CP)atmosphere. Rx gases with LPG (Liquid Petroleum Gas)used to generate the CP atmosphere in gas carburizing process. Continuous gas carburizing furnace is used to perform the case-harden process of the bevel gears. Inner potion of the material having low carbon contents (Carbon 0.13%) so, it’s also hardened up to some extent. In the bevel gear, tooth contact will be in the surface, toughness and wear resistance required in the surface profile, so carburizing is done for bevel gears [16].The cycle time for carburizing and diffusion step was 300 and 120 minutes. For the carburizing step, carbon potential maintained 1.0 % and temperature 940 °C. For the diffusion step, maintained 940 °C temperature and 0.9 wt. %CP. The bevel gears were salt quenched after hardening process, maintained salt temperature 220 °C and cycle time 10 minutes. Finally, gears were done the tempering process with 180 °C temperature and 60 minutes process time. After HT process, Gear surface hardness increased to 60 HRC and the Effective Case Depth(ECD) observed 0.95mm (Hardness cut off value for ECD is 550HV1). Figure 3 and 4 shown a cutting section view and case profile of the carburized gear tooth. Micro surface hardness measured with a SAROJ make hardness testing machine and used load 150Kgs. Polished cut-sections of the gears used for measurement. Uniform case depth achieved all over the surface of the gear teeth. Figures 5 and 6 shown the microstructure images of gear at case and core position after heat treatment.

![Figure 3. Cutting location.](image1)

![Figure 4. Case profile of the gear (5X, 2% Nital etch).](image2)

![Figure 5. Microstructure photos in 200X and 500X at case position.](image3)
3. Shot peening

Case-hardened gears moved to shot peening process after mechanical cleaning by shot blasting. The nozzle assisted shot peening machine as shown in Fig.7 used for peening process. In this equipment peening media (shots) and compressed air was mixed in a pot or tank and flowed through nozzles from rubber hoses. The shots flow rate was controlled by a magnaflo control valve [14]. The nozzle exit diameter of 6 mm and length of 70 mm. Total five stations were available in the machine, two stations were designed as the power station. Shot peening performed in two stations at the same time. Stations were arranged in indexing mechanism. One station used for loading/unloading, another two stations used to carry the parts at before and after the power stations. Table can be rotated in constant 5rpm by using the bottom spur gear engagement. Machine had the auto sieving mechanism, worn-out shots were segregated and removed automatically. Also machine had dust collectors to remove the dust particles. Machine fully controlled by CNC system. All process parameters can be changed by using controller except nozzle distance.

3.1 Nozzle position

The nozzle distance must be sufficient to ensure that the “hot spot” diameter. The blast pattern can be determined by placing a thin section of steel sheet in front of a nozzle separated as shown in fig.9 by a distance of 7 inches. Hot spot diameter must be greater than the maximum tooth length to be peened. Our test sample gear tooth length were 16mm. The steel sheet shot peened with shot only long enough to achieve 100% coverage in the "hot spot", typically in 6 - 10 seconds. Then the pattern was examined, measuring the size of the area that shows 100% dimpling. This process had been repeated, increasing the distance between the nozzles and steel sheet until the measured distance was greater than the maximum tooth length. The nozzles were positioned 9 inches above the test samples, which was perpendicular to the root angle. The above said parameters, hot spot area found 26 mm diameter in the test specimen plate. To improve the coverage, the nozzles were adjusted as shown in Fig. 8.
3.2 Shot peening media
The peening media was a cut wire, small particles of shots were hitting rapidly on the surface of the gears by using pressurized air. Sharp edges should be avoided in the manufacturing of cut wires, this can be helped for uniform indentations. Cut shots are manufactured from high-quality high carbon steel wires, the cut length of the wire is equal to its diameter (1.0 mm) [10]. After wire cutting process, sharp corners were rounded off by using specialized process. Cut shots hardness verified to 650 – 750 HV and finished shot shape is per AMS 2431/8 Section 3.7 for AWCH 41 shot size. Wire diameter 1.0 mm ± 0.02 mm found. Chemical composition of the cut wire as shown in table 2. Hardened fixtures as shown in fig.9 had been used for shot peening process to avoid the worn-out during peening. Rounded profile observed in cut wire shots during checked through stereo microscope.

| Table 2: Chemical composition (%) of Cut wire shots. |
|--------------------------------------------------|
|        | C  | Si  | Mn  | S   | P   | Ni  |
| Min.   | 0.79 | 0.15 | 0.30 | -   | -   | 3.00 |
| Max.   | 0.86 | 0.35 | 0.60 | 0.03 | 0.03 | 3.50 |
| Actual | 0.82 | 0.17 | 0.49 | 0.007 | 0.01 | 3.18 |

3.3 Saturation curve
Test Almen strips, holders, and gauges shall conform to SAE J442 and J443. Specially machined test fixture with gear used for saturation determination. The Almen test blocks were mounted on fixture as shown in Figure 9. To determine saturation, followed the procedure in SAE J443 to generate a saturation curve. Used 40, 80, 160, and 320 second times for saturation curve. Used a fresh test strip for each exposure. Plot the data point for each exposure on a graph. Drawn a smooth best-fit curve using all points. Saturation trial taken as per followed process parameters, Pressure 6bar, Nozzle distance 9 inches and shot flow rate 3kg/min. Almen-C strip used for saturation trial process and Arc height measurement is done by using Almen intensity gauge as shown in figure 15. Saturation is defined as “when the exposure time on the curve is doubled but does not increase the arc height by more than 10%” [13]. It is where the curve starts to level off. Recorded the saturation time and Almen arc height as followed 40sec – 0.18mm, 80sec – 0.186mm, 160sec – 0.20mm and 320sec – 0.21mm. Saturation curve was generated using programmed excel software as attached below shown in table 3. Saturation intensity 0.19 mm achieved in 42.6 seconds.
Table 3: Saturation curve for samples.

4. Coverage and Intensity
Coverage is the measurement that how much area uniformly covered by the shots during shot peening process. The percentage of peening coverage (0 to 100%) were measured by visual methods or using 20X stereoscope examination. Beyond 100% peening coverage can’t be measured by visual methods. When the gear surface being collided more than one times by peening media, 100% coverage be achieved. Coverage is affected by shot’s geometry, work piece hardness and chemistry. The size of the shots were impact on the exposure time of shot peening, where smaller shots produce more impacts on the peening area so, it required lesser time for peening. Soft shots impacts on harden material, take more time to reach the required coverage and shots worn out will be higher compared to hard shots impacting a soft material [14]. Achieved 100% coverage using a low power (typically 10-20x) stereoscope or visual examination at the root and root radius area of the actual gears in 20sec exposure time. As shown in Figures 10 and 11 for the samples of incomplete and complete coverage. A dye marking ink method per SAE J2277 was used to check the coverage. By coated an actual gear with a dye marking ink method as per SAE J2277. The final measurement of coverage was made with the visual and stereo-microscope images.
Arc height
To measure the Almen arc height, first placed the flat face of the calibrated master on Almen gauge as shown in figure 12 and ensured the proper butting on the four supporting pins. Then made zero on the Almen dial gauge, again make sure the zero when placed the Almen strip before peening process. Strip properly located with peening fixture and completed the peening as shown in figure 9. Once finished the peening, Almen strip removed from fixture and firmly seated on the locating pins of Almen gauge. The dial indicator given the reading of deflection called as arc height [15]. Recorded the arc height from various experimental trials and used for analysis. Almen strip should not be reusable. Every time fresh strip must be used for experimental data collection. Intensity data collection was done as per orthogonal L9 array and readings were recorded in the table.

Almen strip
It is a metallic steel strip which is precisely manufactured in the controlled environmental conditions [17]. There are three types of the Almen Strips using to check the intensity of shot peening [17]. In these experiments, ‘C’ type Almen strips were used for arc height testing.

- ’N’ type = 0.031 ± 0.001 Inches - for low intensity
- ’A’ type = 0.051 ± 0.001 Inches - for medium intensity
- ’C’ type = 0.0938 ± 0.001 Inches - for high intensity

Almen intensity
The peening intensity is well-defined as “the measurement of arc height at the coverage of 98 % minimum by using Almen dial gauge” as shown in figure 12 [16]. After shot peening, Almen strip got a curvature towards centre then the strip arc height was measured by using Almen gauge. Followed the above 4.1 measurement procedure for Almen intensity measurement.

5. Experimental design and procedure
For this experimental analysis, MiniTab-17 was used as statistical software with Taguchi’s L9 orthogonal array. To optimize the shot peening parameters the array had been arranged of 3 columns and 4 rows as shown in Table 4. The identified shot peening parameters for these experiments were Air pressure (P), Nozzle distance (D), Shot flow rate (F) and Exposure time (T). The Signal to Noise ratio (S/N) applied on the each levels of process parameters based on Taguchi’s method. The category of quality characteristic, for better and optimum quality characteristic of the process parameters corresponds to the higher S/N ratio. After the detailed analysis of S/N ratio, the optimal grouping of the process parameters can be found out. The process parameters of Air pressure (P), Exposure time (T) and Shot flow rate (F) can be changed as per experimental design requirement by using machine controller during experimental trial. Shot peening machine had a Computer.
Numerical controlling system. All process parameters except Nozzle distance can be adjusted by using machine controller. Also, can be seen the set process parameters in the display monitor. Nozzle distance (D) was adjusted by manual method. Used fresh gears and Almen strips for every experimental trials and samples were identified. Results like Almen intensity, Surface hardness and Surface roughness were taken from experimental samples by using standard measurement technique as discussed earlier and results were recorded. Surface finish measurement done by using Zeiss make surface tester. Microscopic images of indentation at root area of non-peened and peened gears as shown in Figure 13 and 14.

![Figure 13. Non-peened gear image (10X).](image1)

![Figure 14. Peened gear image (10X).](image2)

Table 4: Shot peening design levels and process parameters.

| Process parameters | Code | Unit    | Level 1 | Level 2 | Level 3 |
|--------------------|------|---------|---------|---------|---------|
| A: Air pressure    | P    | Bar     | 5.0     | 5.5     | 6.0     |
| B: Nozzle Distance | D    | Inches  | 9.0     | 10.0    | 11.0    |
| C: Shot flow rate  | F    | Kg/min. | 2.5     | 3.0     | 3.5     |
| D: Exposure time   | T    | Sec.    | 35      | 40      | 45      |

6. Results and Discussion

6.1 Signal to noise ratio (S/N) analysis

Taguchi method is robust and powerful DoE tool for process and product optimization. Signal-to-noise ratio and L9 orthogonal array are the two major analyses tools used in Taguchi’s design. In the manufacturing process design, robust design is important method for improvement [18]. The types of quality characteristics of S/N ratio are, “1. The larger-the-better, 2. The smaller-the-better and 3. The nominal-the-better”[19]. In this experiment, the surface hardness at pitch and root and Almen intensity of the gear should be maximum, so the larger is better type of the S/N ratio had been used. Surface roughness at pitch and root of the gear should be minimum, so the smaller is better type of the S/N ratio had been used. Signal-noise ratio (S/N) were calculated for all controlling factors to minimize the variations in Intensity, Surface hardness at pitch, Surface hardness at root, Surface roughness at pitch, and surface roughness at root values. The suitable signal-to-noise ratio must be selected from past knowledge, and the process understanding.

\[
\frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{3}\frac{1}{Y_{i}^2}\right) \tag{1}
\]
In this experiment, Larger the better was calculated rendering to the Equation (1) and Smaller the better was calculated from the above Equation (2). Where ‘n’ is the number of levels of the experiment is equal to 3 and ‘Yi’ is the result of experiments like Intensity, Surface hardness and Surface roughness. The Taguchi experimental results for Surface roughness (SR) at root and pitch was summarized in Table 5 and represented in Fig. 15 and 16. As shown in Figures, the lowest surface roughness at root and pitch was achieved when Pressure, Distance, Shot flow rate, and Exposure time was chosen according to levels 3, 1, 1, 2 and 1, 3, 2, 2 respectively. The influence of each controlling factors (P, D, F, and T) on the results of surface roughness at root and pitch had been performed with an S/N ratio response table. The Response tables for surface roughness at root and pitch was shown in tables 6 and 7.

**Table 5:** Layout of L9 Orthogonal Array for Surface Roughness at Gear Root and Pitch.

| Exp. No | Air Pressure P (bar) | Distance D (Inch) | Shot Flow Rate F (Kg/min) | Exposure time T (sec) | Surface Roughness – Root (µ Ra) | Surface Roughness – Pitch (µ Ra) | S/N Ratio - Root | S/N Ratio - Pitch |
|---------|----------------------|-------------------|---------------------------|-----------------------|-------------------------------|-------------------------------|----------------|-----------------|
| 1       | 5.0                  | 9                 | 2.5                       | 35                    | 2.013                         | 1.500                         | -6.07688       | -3.52183        |
| 2       | 5.0                  | 10                | 3.0                       | 40                    | 1.676                         | 1.639                         | -4.48548       | -4.29158        |
| 3       | 5.0                  | 11                | 3.5                       | 45                    | 1.664                         | 1.649                         | -4.42307       | -4.34441        |
| 4       | 5.5                  | 9                 | 3.0                       | 45                    | 2.226                         | 1.629                         | -6.95050       | -4.23842        |
| 5       | 5.5                  | 10                | 3.5                       | 35                    | 1.539                         | 1.154                         | -3.74477       | -1.24412        |
| 6       | 5.5                  | 11                | 2.5                       | 40                    | 2.258                         | 1.522                         | -7.07448       | -3.64829        |
| 7       | 6.0                  | 9                 | 3.5                       | 40                    | 2.017                         | 1.733                         | -6.09412       | -4.77597        |
| 8       | 6.0                  | 10                | 2.5                       | 45                    | 1.990                         | 1.139                         | -5.97706       | -1.13047        |
| 9       | 6.0                  | 11                | 3.0                       | 35                    | 2.009                         | 1.802                         | -6.05960       | -5.11510        |

**Table 6:** The response table for Surface Roughness at Root (Smaller is Better).

| Process parameters | Level 1 | Level 2 | Level 3 | Delta | Rank |
|--------------------|---------|---------|---------|-------|------|
| A - Air Pressure   | -4.995  | -5.923  | -6.044  | 1.048 | 3    |
| B - Distance       | -6.374  | -4.736  | -5.852  | 1.638 | 1    |
| C - Shot Flow Rate | -6.376  | -5.832  | -4.754  | 1.622 | 2    |
| D - Exposure time  | -5.294  | -5.885  | -5.784  | 0.591 | 4    |
Table 7: The response table for Surface Roughness at Pitch (Smaller is Better).

| Factors          | Level 1 | Level 2 | Level 3 | Delta | Rank |
|------------------|---------|---------|---------|-------|------|
| A-Air Pressure   | -4.053  | -3.044  | -3.674  | 1.009 | 3    |
| B-Distance       | -4.174  | -2.222  | -4.369  | 2.147 | 1    |
| C-Shot Flow Rate | -2.767  | -4.548  | -3.455  | 1.782 | 2    |
| D-Exposure time  | -3.294  | -4.239  | -3.238  | 1.001 | 4    |

The experimental results for Surface hardness (SH) at root and pitch was summarized in Table 8 and represented in Fig. 15 and 16. As shown in Figures, the highest surface hardness at root and pitch was achieved when Pressure, Distance, Shot flow rate, and Exposure time was chosen according to levels 3, 1, 3, 2 and 2, 3, 3, 3 respectively. The influence of each controlling factors (P, D, F, and T) on the results of surface hardness at root and pitch had been performed with an S/N ratio response table. The response tables for surface hardness at root and pitch was shown in tables 9 and 10.

Figure 15. Main effect of S/N ratio vs. input parameters for SR at root.
Figure 16. Main effect of S/N ratio vs. input parameters for SR at pitch.

Table 8: Layout of L9 Orthogonal Array for Surface Hardness at Gear Root and Pitch.

| Exp. No | Air Pressure P (bar) | Distance D (Inch) | Shot Flow Rate F (Kg/min) | Exposure time T (sec) | Surface Hardness – Root (HRC) | Surface Hardness – Pitch (HRC) | S/N Ratio - Root | S/N Ratio - Pitch |
|---------|----------------------|-------------------|---------------------------|----------------------|------------------------------|------------------------------|------------------|------------------|
| 1       | 5.0                  | 9                 | 2.5                       | 35                   | 61.9                         | 61.9                         | 35.8338          | 35.8338          |
| 2       | 5.0                  | 10                | 3.0                       | 40                   | 61.5                         | 60.5                         | 35.7704          | 35.6351          |
| 3       | 5.0                  | 11                | 3.5                       | 45                   | 62.3                         | 63.2                         | 35.8898          | 36.0075          |
| 4       | 5.5                  | 9                 | 3.0                       | 45                   | 62.3                         | 62.2                         | 35.8898          | 35.8758          |
| 5       | 5.5                  | 10                | 3.5                       | 35                   | 61.8                         | 61.5                         | 35.8127          | 35.7704          |
| 6       | 5.5                  | 11                | 2.5                       | 40                   | 62.3                         | 61.9                         | 35.8828          | 35.8338          |
| 7       | 6.0                  | 9                 | 3.5                       | 40                   | 62.9                         | 61.9                         | 35.9661          | 35.8338          |
| 8       | 6.0                  | 10                | 2.5                       | 45                   | 61.7                         | 61.4                         | 35.8057          | 35.7634          |
| 9       | 6.0                  | 11                | 3.0                       | 35                   | 61.9                         | 61.7                         | 35.8268          | 35.8057          |
Table 9: The response table for Surface Hardness at Root (Larger is Better).

| Process parameters | Level 1 | Level 2 | Level 3 | Delta | Rank |
|--------------------|---------|---------|---------|-------|------|
| A- Air Pressure    | 35.83   | 35.83   | 35.80   | 0.03  | 4    |
| B- Distance        | 35.85   | 35.72   | 35.88   | 0.16  | 1    |
| C- Shot Flow Rate  | 35.81   | 35.77   | 35.87   | 0.10  | 3    |
| D- Exposure time   | 35.80   | 35.77   | 35.88   | 0.11  | 2    |

Table 10: The response table for Surface Hardness at Pitch (Larger is Better).

| Process parameters | Level 1 | Level 2 | Level 3 | Delta | Rank |
|--------------------|---------|---------|---------|-------|------|
| A- Air Pressure    | 35.85   | 35.88   | 35.83   | 0.05  | 4    |
| B- Distance        | 35.88   | 35.75   | 35.92   | 0.17  | 1    |
| C- Shot Flow Rate  | 35.85   | 35.79   | 35.91   | 0.12  | 2    |
| D- Exposure time   | 35.84   | 35.82   | 35.88   | 0.06  | 3    |

Figure 17: Main effect of S/N ratio vs. input parameters for SH at root.
Figure 18. Main effect of S/N ratio vs. input parameters for SHat pitch.

The experimental results for Almen intensity (AI) were summarized in Table 11 and represented in Fig. 19. As shown in Figure, the highest Almen intensity was achieved when Pressure, Distance, Shot flow rate, and Exposure time was chosen according to levels 3, 3, 1, and 3 respectively. The influence of each controlling factors (P, D, F, and T) on results of the Almen intensity had been performed with an S/N ratio response table. The response table for Almen intensity was shown in Table 12.

Table 11: Layout of L9 Orthogonal Array for Almen Intensity.

| Exp.No | Air Pressure P (bar) | Distance D (Inch) | Shot Flow Rate F (Kg/min) | Exposure time T (sec) | Intensity Almen - C (mm) | S/N Ratio - Intensity |
|--------|----------------------|-------------------|---------------------------|-----------------------|------------------------|----------------------|
| 1      | 5.0                  | 9                 | 2.5                       | 35                    | 0.161                  | -15.8635             |
| 2      | 5.0                  | 10                | 3.0                       | 40                    | 0.164                  | -15.7031             |
| 3      | 5.0                  | 11                | 3.5                       | 45                    | 0.169                  | -15.4423             |
| 4      | 5.5                  | 9                 | 3.0                       | 45                    | 0.170                  | -15.3910             |
| 5      | 5.5                  | 10                | 3.5                       | 35                    | 0.175                  | -15.1392             |
| 6      | 5.5                  | 11                | 2.5                       | 40                    | 0.183                  | -14.7510             |
| 7      | 6.0                  | 9                 | 3.5                       | 40                    | 0.176                  | -15.0897             |
| 8      | 6.0                  | 10                | 2.5                       | 45                    | 0.191                  | -14.3793             |
| 9      | 6.0                  | 11                | 3.0                       | 35                    | 0.188                  | -14.5168             |
Table 12: The response table for Almen Intensity (Larger is Better).

| Factors          | Level 1 | Level 2 | Level 3 | Delta | Rank |
|------------------|---------|---------|---------|-------|------|
| A-Air Pressure   | -15.67  | -15.09  | -14.66  | 1.01  | 1    |
| B-Distance       | -15.45  | -15.07  | -14.90  | 0.54  | 2    |
| C-Shot Flow Rate | -15.00  | -15.20  | -15.22  | 0.23  | 3    |
| D-Exposure time  | -15.17  | -15.18  | -15.07  | 0.11  | 4    |

Figure 19. Main effect of S/N ratio vs. input parameters for AI.

7. Conclusions

The current experimental study was aimed to find out the optimum and greatest influencing process parameters in the following results of Surface roughness at root and pitch, Surface hardness at root and pitch and Almen intensity. The result was found from the minimum number of experimental trials using Taguchi’s L9 orthogonal array. Several combinations of peening parameters were measured to find out the comparative importance of the parameters. Determination of S/N ratio from experimental trials was initial step of the optimization process. “Larger values of the signal-to-noise ratio (S/N) were identified the control factor settings that minimized the effects of the noise factors”. The following step was found out the response of independent parameters to the final results. “The response table of S/N ratio contained a column for the average ratio for each factor level, Delta, and Rank. The highest rank was given to the maximum delta value of the response table also known as greatest influencing parameter. “The main effects plots shown how each factors affected the response characteristics”. Smaller is better used in main effect plots for the results of Surface roughness at root and pitch. Larger is better used in main effect plots for the results of Surface hardness at root, pitch and Almen intensity. According to final results, the following conclusions can be summarized,

- The optimized shot peening process parameters for Surface roughness at root are: Air pressure (P) 6 bar, Nozzle distance (D) 9 inches, Shot flow rate (F) 2.5 Kg/min and Exposure time (T) 40 sec.
From the selected independent process parameters, **Nozzle distance (D)** is found to be the greatest influencing parameter for Surface roughness at root trailed by Shot flow rate (F), Air pressure (P) and Exposure time (T). The results are represented in response table 6.

The optimized shot peening process parameters for Surface roughness at pitch are: Air pressure (P) 5 bar, Nozzle distance (D) 11 inches, Shot flow rate (F) 3.0 Kg/min and Exposure time (T) 40sec.

From the selected independent process parameters, **Nozzle distance (D)** is found to be the greatest influencing parameter for Surface roughness at pitch trailed by Shot flow rate (F), Air pressure (P), and Exposure time (T). The results are represented in response table 7.

The optimized shot peening process parameters for Surface hardness at root are: Air pressure (P) 6 bar, Nozzle distance (D) 9 inches, Shot flow rate (F) 3.5 Kg/min and Exposure time (T) 40sec.

From the selected independent process parameters, **Nozzle distance (D)** is found to be the greatest influencing parameter for Surface hardness at root trailed by Exposure time (T), Shot flow rate (F) and Air pressure (P). The results are represented in response table 9.

The optimized shot peening process parameters for Surface hardness at pitch are: Air pressure (P) 5.5 bar, Nozzle distance (D) 11 inches, Shot flow rate (F) 3.5 Kg/min and Exposure time (T) 45sec.

From the selected independent process parameters, **Nozzle distance (D)** is found to be the greatest influencing parameter for Surface hardness at pitch trailed by Exposure time (T) and Air pressure (P). The results are represented in response table 10.

The optimized shot peening process parameters for Almen intensity are: Air pressure (P) 6 bar, Nozzle distance (D) 11 inches, Shot flow rate (F) 2.5 Kg/min and Exposure time (T) 45sec.

From the selected independent process parameters, **Air pressure (P)** is found to be the greatest influencing parameter for Almen intensity trailed by Nozzle distance (D), Shot flow rate (F) and Exposure time (T). The results are represented in response table 12.

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