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Influence of Polishing and Post-Oxidation Parameters on Surface Roughness of QPQ-Treated EN8 Steel: A Taguchi Design Study

Sushil B. Chopade *, Amit Tiwari, Neeraj Kumar and Ganesh Lohar

Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur Rajasthan, India.

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Abstract

Gas spring piston rods operate under repetitive sliding contact, fluctuating mechanical loads, and exposure to aggressive environmental conditions, making surface integrity a key determinant of durability and functional reliability. Quench–Polish–Quench (QPQ) salt bath nitriding is an advanced thermochemical treatment widely employed to improve the surface characteristics of steel components through enhanced hardness, wear resistance, and corrosion protection. This study examines the effect of polishing grit size, oxidation duration, and oxidation temperature on the surface roughness of QPQ-treated EN8 steel used for gas spring piston rod applications. All specimens were nitrided at 570°C for 180 min, followed by polishing and post-oxidation treatments designed according to a Taguchi L9 orthogonal array. Surface roughness measurements were carried out using a Mitutoyo SJ-410 profilometer. The experimental data were analyzed using Signal-to-Noise (S/N) ratio methodology and Analysis of Variance (ANOVA) to identify the most significant process variables and determine optimum operating conditions. The results demonstrated that polishing grit size had the greatest influence on surface finish, while oxidation temperature and oxidation time exhibited comparatively lower effects. The lowest average surface roughness of 0.12 µm was achieved using a polishing grit size of 1200, oxidation time of 30 min, and oxidation temperature of 380°C. The optimized treatment parameters produced a smoother and more uniform surface morphology, which is desirable for improving the tribological performance and service life of gas spring piston rods. The outcomes of this investigation provide valuable guidance for the industrial optimization of QPQ salt bath nitriding processes for EN8 steel components.

Keywords: EN8 steel; QPQ salt bath nitriding; Surface roughness; Taguchi optimization; ANOVA; Oxidation treatment; Gas spring piston rod; Surface engineering

1. Introduction

Gas springs are extensively used in automotive tailgates, industrial machinery, medical equipment, furniture systems, and aerospace applications because of their ability to provide controlled motion and load support. The piston rod is a critical component of a gas spring as it operates under continuous reciprocating motion and cyclic loading while being exposed to humid and corrosive service environments. The operational reliability and service life of gas springs are largely governed by the surface integrity of the piston rod. Inadequate surface hardness, poor wear resistance, and insufficient corrosion protection can lead to seal damage, increased friction, gas leakage, and premature failure. Therefore, enhancement of surface properties through advanced surface engineering techniques has become essential for improving the durability and performance of gas spring piston rods [1], [2]

EN8 steel is widely employed for manufacturing gas spring piston rods due to its good strength, machinability, and economic viability. However, untreated EN8 steel often exhibits limited resistance to wear and corrosion under severe operating conditions. To overcome these limitations, thermochemical surface modification processes such as nitriding

* Corresponding author: Sushil B. Chopade

and nitrocarburizing are frequently applied. Among these techniques, Quench–Polish–Quench (QPQ) salt bath nitriding has gained considerable industrial acceptance because it simultaneously improves surface hardness, wear resistance, fatigue strength, and corrosion resistance without significantly affecting the core mechanical properties of the component [3], [4], [5], [6]. The QPQ process consists of three successive stages: nitriding, polishing, and post-oxidation. During nitriding, nitrogen diffuses into the steel surface, producing a compound layer primarily consisting of ε-$Fe_{2-3}N$ and γ'-Fe_4N phases together with an underlying diffusion zone. This modified surface structure significantly increases hardness and resistance to abrasive wear. The polishing stage removes loosely adhered compounds and surface asperities, thereby improving surface finish. Finally, post-oxidation generates a compact magnetite (Fe_3O_4) layer that enhances corrosion resistance and reduces friction. The combined effect of these treatments results in superior tribological and corrosion-resistant properties compared with conventional heat-treatment methods [7], [8]Surface roughness is one of the most important functional characteristics of gas spring piston rods. A smoother surface promotes effective sealing, reduces friction between the rod and sealing elements, minimizes wear, and improves corrosion resistance. Excessive roughness can create stress concentration sites and increase the probability of localized corrosion and seal degradation. Consequently, optimization of finishing parameters after QPQ treatment is necessary to obtain the surface quality required for long-term service performance [9], [10]. Although considerable research has been conducted on hardness enhancement, wear resistance, fatigue performance, and corrosion behavior of nitrided steels, limited studies have focused on the optimization of surface roughness in QPQ-treated EN8 steel. Furthermore, the combined influence of polishing grit size, oxidation time, and oxidation temperature on the final surface finish of gas spring piston rods has not been adequately investigated. Therefore, a systematic experimental study employing statistical optimization techniques is required to establish suitable processing conditions for industrial applications.

In the present investigation, the effects of polishing grit size, oxidation time, and oxidation temperature on the surface roughness of QPQ salt bath nitrided EN8 steel are evaluated using a Taguchi L9 orthogonal array. Signal-to-Noise ratio analysis and Analysis of Variance (ANOVA) are employed to determine the significance of individual process parameters and identify the optimum treatment conditions for gas spring piston rod applications.

2. Literature Review

Surface modification through nitriding and nitrocarburizing processes has been extensively investigated to improve the wear resistance, fatigue strength, corrosion resistance, and tribological performance of engineering steels. Among these techniques, Quench–Polish–Quench (QPQ) salt bath nitriding has emerged as an effective thermochemical treatment capable of producing a hard compound layer, a diffusion zone, and a protective oxide layer. The process has found widespread applications in automotive, tooling, aerospace, and mechanical engineering components where superior surface properties are required.

Investigation of liquid nitriding of 316 stainless steel reported that nitriding temperature and treatment duration significantly influenced the thickness of the nitrided layer.The authors observed the formation of chromium nitrides and iron nitride phases, which enhanced fatigue resistance through the generation of compressive residual stresses and inhibition of crack propagation[11]. Similarly, evaluation of the erosion-corrosion behavior of low-temperature nitrided 316L stainless steel and demonstrated substantial improvements in resistance to surface degradation under aggressive environments.[12]The influence of surface treatment on fatigue performance has been comprehensively reviewed and concluded that appropriate heat-treatment parameters can significantly enhance fatigue life and surface hardness of steels subjected to cyclic loading conditions[13]. Investigation of the fretting wear behavior of nitrided 316L stainless steel reported that nitrided surfaces exhibited improved wear resistance and smoother worn surface morphology compared with untreated materials.[14]

The importance of process optimization in salt bath nitriding was highlighted and performed a failure analysis of nitrided 316L stainless steel valves. Study revealed that excessive nitriding and improper process control can generate microcracks and brittle compounds within the nitrided layer, resulting in premature corrosion failure. The authors emphasized the need for careful selection of nitriding parameters to achieve optimal performance.[5]

Several studies have specifically investigated the QPQ process and its effect on wear and corrosion properties. The influence of nitriding duration was examined on 45 carbon steel treated by QPQ salt bath nitriding. The study demonstrated that nitriding time significantly affected compound layer formation, hardness, wear resistance, and corrosion behavior. The highest surface hardness of approximately 630 HV was achieved after nitriding for 120 min, while the optimum corrosion and wear performance were obtained at different nitriding durations. The formation of a thin Fe_3O_4 oxide layer during post-oxidation was identified as a major contributor to corrosion protection.[15]

A review compared salt bath nitriding and gas nitriding treatments for AISI 347 steel. The authors reported that both processes improved wear resistance; however, the selection of treatment conditions strongly influenced the resulting surface characteristics and tribological behavior.[16]

Of particular relevance to the present investigation, study on the effect of salt bath nitriding on the surface roughness behavior of AISI 4140 steel observed that nitriding treatment significantly increased surface hardness through the formation of ε-Fe_{2-3}(N,C) and γ'-Fe_4(N,C) phases. However, increasing nitriding time also increased roughness parameters (Ra, Rq, and Rz), indicating a strong relationship between process conditions and surface finish. Their findings emphasize the importance of controlling post-treatment operations to achieve desirable roughness characteristics.[17].Investigation of the effect of QPQ treatment on H13 die steel and reported the formation of a dense compound layer and diffusion zone after nitriding. The major phases identified were $Fe_{2-3}N$ and Fe_3O_4, which substantially improved hardness and wear resistance. The study also showed that excessive nitriding durations resulted in a loose compound layer structure, indicating that process optimization is essential for obtaining superior surface quality and mechanical performance.[18]

The collective findings of previous studies indicate that nitriding parameters such as temperature, treatment duration, and oxidation conditions significantly influence microstructure, hardness, wear resistance, and corrosion performance. However, most published investigations have focused primarily on nitriding duration and temperature, whereas comparatively little attention has been devoted to the combined effects of polishing grit size and post-oxidation parameters on the surface roughness of QPQ-treated steels. Furthermore, no systematic study has been reported on EN8 steel used in gas spring piston rod applications employing statistical optimization techniques such as the Taguchi method and Analysis of Variance (ANOVA). Therefore, the present paper addresses this gap by investigating the influence of polishing grit size, oxidation time, and oxidation temperature on the surface roughness of QPQ-treated EN8 steel. A Taguchi L9 experimental design is adopted to identify the optimum process parameters capable of producing a smooth surface suitable for gas spring piston rod applications.

3. Materials and Experimental Methodology

3.1. Material Selection

EN8 medium-carbon steel was selected as the substrate material for the present investigation due to its widespread utilization in gas spring piston rods, shafts, machine components, and automotive applications requiring a combination of high strength, toughness, and good machinability. The steel exhibits favourable mechanical properties and responds effectively to thermochemical surface treatments such as nitriding and nitrocarburizing, making it a suitable candidate for QPQ surface modification [11][15] The nominal chemical composition of EN8 steel is presented in *Table 1.*

Table 1 Chemical Composition of EN8 Steel

Element	Composition (wt %)
Carbon (C)	0.36–0.44
Manganese (Mn)	0.60–1.00
Silicon (Si)	0.10–0.40
Iron (Fe)	Balance

The selected material is commonly employed in gas spring piston rods because of its ability to maintain adequate core strength while allowing significant enhancement of surface properties through nitriding treatments [16]

3.2. Sample Preparation

Experimental specimens were machined from commercially available EN8 steel bars into ø 10 mm for QPQ salt bath nitriding and surface roughness evaluation. The machined samples were initially ground to remove machining marks and surface irregularities. Prior to nitriding, all specimens underwent thorough cleaning using acetone followed by deionized water in an ultrasonic cleaning system to eliminate oil residues, dust particles, and other contaminants that could adversely affect nitrogen diffusion during the nitriding process [12] After cleaning, the specimens were air dried and stored under controlled laboratory conditions before undergoing the QPQ treatment cycle.

3.3. QPQ Salt Bath Nitriding Process

The surface modification of EN8 steel specimens was performed using the Quench–Polish–Quench (QPQ) salt bath nitriding process, a thermochemical surface engineering technique widely employed to improve surface hardness, wear resistance, fatigue performance, and corrosion resistance of engineering steels[1]. The complete treatment cycle adopted in the present investigation is illustrated in Figure 1.

3.3.1. Preheating

Initially, the machined EN8 steel specimens were preheated in air at a temperature range of 350–400°C, as shown in Figure 1. The primary objective of this stage was to remove residual moisture, oils, and surface contaminants while ensuring uniform temperature distribution throughout the specimen. Proper preheating minimizes thermal shock during immersion into the molten salt bath and promotes uniform diffusion of nitrogen and carbon during the subsequent nitrocarburizing stage[19][2]

3.3.2. Salt Bath Nitrocarburizing

Following preheating, the specimens were immersed in a molten cyanate/cyanide salt bath maintained at 570°C. At this temperature, active nitrogen and carbon atoms diffuse into the steel surface, resulting in the formation of a hard compound layer (white layer) composed predominantly of ε-$Fe_{2-3}N$ and γ′-Fe_4N phases along with an underlying diffusion zone [1]. The compound layer provides excellent wear resistance, whereas the diffusion zone enhances load-bearing capacity and fatigue strength. To investigate the influence of treatment duration, nitrocarburizing was conducted for 180 min. Previous studies have reported that increasing nitriding time increases the thickness of both the compound layer and diffusion zone, leading to significant changes in hardness, surface morphology, and tribological performance.

3.3.3. Oxidation Cooling

After completion of nitrocarburizing, the specimens were transferred to an oxidation-cooling stage maintained between 380–430°C (Figure. 1). This intermediate treatment stabilizes the nitrided layer and prepares the surface for subsequent polishing. Controlled cooling is essential to avoid thermal stresses and preserve the integrity of the compound layer [20]

3.3.4. Mechanical Polishing

The nitrided specimens were then polished sequentially using 800 grit, 1000 grit, and 1200 grit silicon carbide abrasive papers, as illustrated in Figure. 1. Mechanical polishing removes loosely adhered surface deposits generated during nitrocarburizing and reduces surface irregularities without significantly affecting the nitride layer thickness. This step improves surface finish, dimensional accuracy, and the uniformity of the subsequent oxide layer formation [17].

3.3.5. Post-Oxidation Treatment

The polished specimens were subjected to a final post-oxidation treatment to enhance corrosion resistance. Three oxidation conditions were investigated380°C for 15 min,400°C for 30 min and 420°C for 45 min

During post-oxidation, a dense and adherent Fe_3O_4 (magnetite) layer forms on the nitrided surface. This oxide layer acts as a protective barrier against corrosive environments and contributes to improved wear resistance by reducing friction and preventing direct metal-to-metal contact. The combined effect of nitrocarburizing and post-oxidation is responsible for the superior corrosion and tribological performance characteristic of the QPQ process.[20], [21]. The complete QPQ cycle adopted in this study is schematically presented in Fig. 1, highlighting the preheating, nitrocarburizing, oxidation cooling, polishing, and post-oxidation stages used for surface modification of EN8 steel.

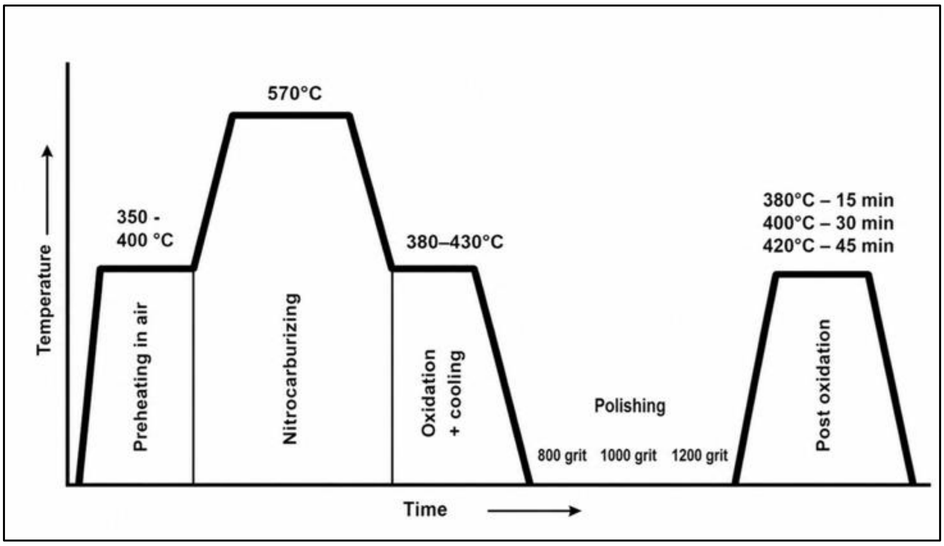

Figure 1 Schematic representation of the QPQ salt bath nitriding cycle employed for EN8 steel, consisting of preheating (350–400°C), nitrocarburizing (570°C) for 180 mins, oxidation cooling (380–430°C), polishing using 800, 1000 and 1200 grit abrasive papers, and post-oxidation (380–420°C)

3.4. Surface Roughness Measurement

The surface roughness of untreated and nitrided EN8 steel specimens was evaluated using a stylus-type surface profilometer, which is a widely accepted instrument for precise measurement of surface topography. The parameter selected for analysis was the arithmetic average roughness (Ra), as it provides a reliable indication of the average surface deviation and is commonly used in engineering applications to assess surface quality.

The arithmetic average roughness (Ra) is defined as:

$$R_a = \frac{1}{n}\sum_{i=0}^{n}|Y_i|$$

Where Y_i Represents the vertical deviation of individual points from the mean line, and n is the total number of sampling points considered over the evaluation length. For each nitriding condition. Five different samples were tested, and for each sample, surface roughness measurements were recorded at multiple locations to ensure repeatability and accuracy. The readings obtained (S1–S5) represent the surface condition at different positions on the specimen, thereby minimizing localized measurement errors and providing a more representative assessment of the surface profile.

The average surface roughness value for each nitriding condition was calculated by taking the mean of the five readings. This averaging approach reduces experimental uncertainty and ensures statistical reliability of the measured data. It has been reported in earlier studies that multiple measurements across the specimen surface are essential for accurate characterization of roughness, particularly in nitride materials where surface heterogeneity may arise due to diffusion processes and compound layer formation [22]

Furthermore, the stylus-based measurement technique enables the detection of micro-level surface irregularities formed during nitriding and post-oxidation processes. The variation in Ra values with respect to nitriding time provides insight into the evolution of surface morphology, which is influenced by compound layer growth, diffusion depth, and oxide layer formation

4. Result and Discussion

To systematically investigate the influence of process parameters on the surface roughness of QPQ salt bath nitrided EN8 steel, the Taguchi Design of Experiments (DOE) approach was employed. Taguchi methodology is widely used in engineering optimization studies because it reduces the number of experimental trials while maintaining the ability to evaluate the effects of multiple process parameters simultaneously. In addition, it provides a robust statistical framework for identifying the optimal process conditions and determining the relative significance of each factor. In the present study, three process parameters were selected as control factors based on their expected influence on the final surface finish of the nitrided specimens. These factors were polishing grit size, post-oxidation time, and post-oxidation temperature. Each factor was investigated at three levels, as presented in Table 2

Table 2 Process parameters and levels used in Taguchi experimental design

Factor	Level 1	Level 2	Level 3
Polishing Grit Size	800	1000	1200
Post-Oxidation Time (min)	15	30	45
Post-Oxidation Temperature (°C)	380	400	420

Since three factors with three levels each were considered, a Taguchi L9 orthogonal array was selected for experimental planning. The L9 array reduces the required number of experiments from 27 (3^3) in a full factorial design to only 9 experimental runs, thereby minimizing experimental effort, material consumption, and testing time while preserving the statistical validity of the study.

The experimental matrix generated using the L9 orthogonal array is presented in Table 3. Each experimental run represents a unique combination of polishing grit size, oxidation time, and oxidation temperature. After completion of the QPQ treatment according to the specified parameter combinations, the surface roughness (Ra) of each specimen was measured and analysed to determine the effect of individual process parameters and to identify the optimum conditions for achieving minimum surface roughness

Table 3 Taguchi L9 Orthogonal Array for QPQ-treated EN8 Steel

Experiment No.	Grit Size	Oxidation Time (min)	Oxidation Temperature (°C)
1	800	15	380
2	800	30	400
3	800	45	420
4	1000	15	380
5	1000	30	420
6	1000	45	400
7	1200	15	420
8	1200	30	380
9	1200	45	400

The experimental results obtained from the above Taguchi design were subsequently analyzed using average surface roughness values, signal-to-noise (S/N) ratios, and analysis of variance (ANOVA) to determine the optimum combination of process parameters and their contribution toward surface quality improvement.

4.1. Surface Roughness Results

The average surface roughness (Ra) values obtained for the QPQ salt bath nitrided EN8 steel specimens under different polishing and post-oxidation conditions are presented in Table X. Surface roughness is an important parameter influencing the tribological performance, fatigue behavior, and corrosion resistance of nitrided components.

Table 4 Experimental Results for Surface Roughness

Experiment No	Polishing Grit	Oxidation Time(Min)	Oxidation Temperature(^{0}C)	Average Ra ((µm)
1	800	15	380	0.45
2	800	30	400	0.47
3	800	45	420	0.48
4	1000	15	380	0.25
5	1000	30	400	0.31
6	1000	45	420	0.33
7	1200	15	380	0.17
8	1200	30	400	0.12
9	1200	45	420	0.19

The results indicate that the polishing grit size had a significant influence on the final surface finish. Specimens polished with 800 grit abrasive paper exhibited the highest roughness values, ranging from 0.45 µm to 0.48 µm. The highest roughness value of 0.48 µm was observed for the specimen subjected to post-oxidation at 420°C for 45 min (Experiment 3), whereas the lowest roughness within this group was 0.45 µm at 380°C for 15 min (Experiment 1). The relatively coarse abrasive particles of 800 grit produced deeper surface scratches, resulting in a rougher surface morphology.

A noticeable reduction in surface roughness was observed when the polishing grit size was increased to 1000 grit. The average Ra values decreased to a range of 0.25–0.33 µm. Experiment 4, performed at 380°C for 15 min, exhibited the lowest roughness value within this group (0.25 µm), indicating that finer polishing effectively removed surface asperities generated during the nitrocarburizing stage. The smoothest surfaces were obtained using 1200 grit polishing, where the roughness values ranged from 0.12 µm to 0.19 µm. The minimum surface roughness of 0.12 µm was achieved in Experiment 8, corresponding to 1200 grit polishing followed by post-oxidation at 380°C for 30 min. Compared with the specimen polished using 800 grit under similar conditions, this represents a reduction in roughness of approximately 73%, demonstrating the effectiveness of finer polishing in producing a smoother and more uniform surface. The post-oxidation parameters also influenced the surface roughness. In general, increasing oxidation temperature and duration resulted in a slight increase in Ra values. This behavior may be attributed to the growth of the Fe_3O_4 oxide layer during post-oxidation, which can increase surface irregularities when formed at higher temperatures and longer oxidation times. However, the effect of polishing grit size was found to be more dominant than the post-oxidation parameters.

Overall, the results demonstrate that the combination of 1200 grit polishing and post-oxidation at 380°C for 30 min produced the best surface finish among all experimental conditions investigated. The improved surface quality is expected to contribute positively to wear resistance, friction behavior, and corrosion performance of QPQ-treated EN8 steel components used in gas spring piston rod applications.

4.2. Signal to Noise Ratio

Since the objective of the present study was to minimize surface roughness, the Smaller-the-better quality characteristic was selected for S/N ratio analysis. The S/N ratio was calculated using:

$$S/N = -10 \log_{10}[(1/n)\ \Sigma(Y^2)]$$

where Y represents the measured surface roughness value.

The response table for S/N ratios obtained from Minitab showed that polishing grit size exerted the highest influence on surface roughness with a Delta value of 9.531, followed by oxidation time (1.585) and oxidation temperature (0.999). The ranking of the factors was therefore:

- Polishing Grit Size
- Oxidation Time
- Oxidation Temperature

The highest S/N ratio was obtained at:

- Polishing Grit Size = 1200 grit (Level 3)
- Oxidation Time = 30 min (Level 2)
- Oxidation Temperature = 380°C (Level 1)

This optimum combination (A3B2C1) corresponds to the condition producing minimum surface roughness and maximum process robustness. Figure 2 presents the main effects plot for S/N ratios. The steep slope observed for polishing grit size confirms its dominant influence on the response.

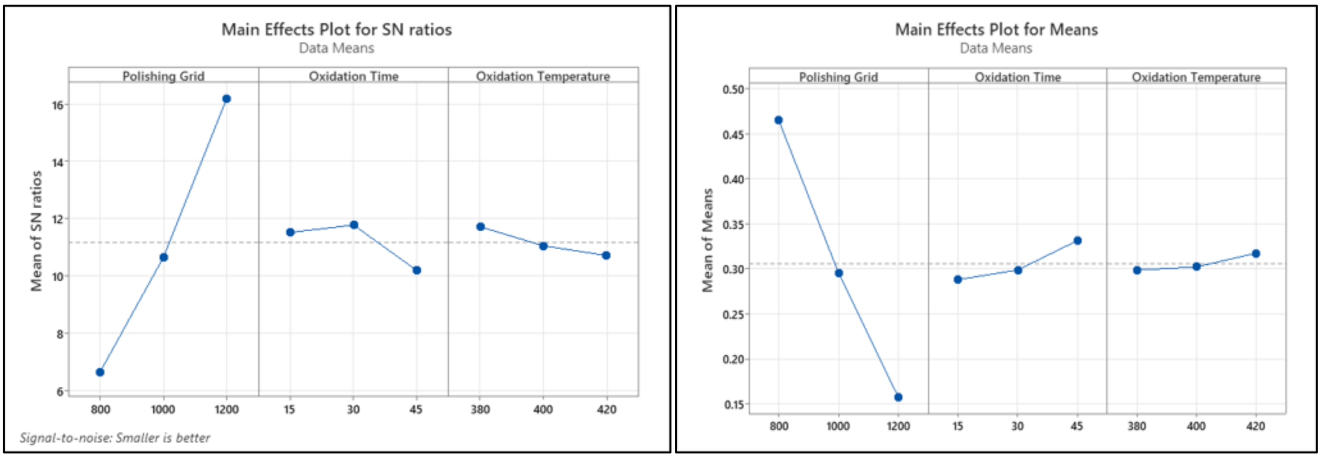

Figure 2 Main Effect Plot for S/N Ratios and main effect flot for Means

The main effects plot for means obtained from Minitab is presented in Figure 2 The plot clearly demonstrates a substantial reduction in surface roughness with increasing polishing grit size. The response table for means indicates that the average surface roughness decreased from 0.4647 μm at 800 grit to 0.1580 μm at 1200 grit, representing a reduction of approximately 66%. The Delta values obtained from the response table were:

- Polishing Grit Size = 0.3067
- Oxidation Time = 0.0433
- Oxidation Temperature = 0.0187

These values further confirm that polishing grit size was the most influential process parameter affecting surface roughness. Oxidation time and oxidation temperature exhibited comparatively smaller effects. Increasing oxidation time from 15 min to 45 min resulted in a slight increase in surface roughness, while increasing oxidation temperature from 380°C to 420°C also produced marginally rougher surfaces due to enhanced oxide layer growth.The optimum condition identified from the main effects plots was:

1200 grit polishing + 30 min oxidation time + 380°C oxidation temperature**.**

Table 5 Response Table for Signal to Noise Ratio

Level	Polishing Grid	Oxidation Time	Oxidation Temperature
1	6.660	11.526	11.722
2	10.657	11.783	11.062
3	16.191	10.198	10.724
Delta	9.531	1.585	0.999
Rank	1	2	3

4.3. Analysis of Variance (ANOVA)

ANOVA was performed to determine the statistical significance of each process parameter. The results obtained from Minitab revealed that polishing grit size was the only statistically significant factor influencing surface roughness.

The ANOVA results shown in Table 6

Since the P-value for polishing grit size was less than 0.05, it was considered statistically significant at the 95% confidence level. The percentage contribution of each factor was estimated from the sum of squares values:

- Polishing Grit Size ≈ 95.5%
- Oxidation Time ≈ 2.1%
- Oxidation Temperature ≈ 0.4%

These results indicate that the final surface finish of QPQ-treated EN8 steel is predominantly controlled by the polishing stage rather than the oxidation parameters. The Taguchi model exhibited an R^2 value of 97.99%, indicating excellent agreement between the experimental data and model predictions.

Table 6 ANOVA for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Polishing Grid	2	0.141579	0.141579	0.070789	47.45	0.021
Oxidation Time	2	0.003059	0.003059	0.001529	1.03	0.494
Oxidation Temperature	2	0.000595	0.000595	0.000297	0.20	0.834
Residual Error	2	0.002984	0.002984	0.001492		
Total	8	0.148216				

4.4. Regression Analysis

A multiple linear regression model was developed to establish the relationship between process parameters and surface roughness.

$$Ra = 0.843 - 0.000767(PG) + 0.001444(OT) + 0.000467(T)$$

Where;
Ra = Surface Roughness (μm)
PG = Polishing Grit Size
OT = Oxidation Time (min)
T = Oxidation Temperature (°C)

The regression model exhibited:

Table 7 Regression Summery

S	R-sq	R-sq(adj)	R-sq(pred)
0.0276043	97.43%	95.89%	89.91%

The negative coefficient associated with polishing grit size confirms that increasing grit size decreases surface roughness, whereas oxidation time and oxidation temperature show a slight positive influence.

The regression ANOVA yielded an F-value of 63.17 and P-value < 0.001, confirming the adequacy of the developed model for predicting surface roughness within the investigated process range. Based on the Taguchi optimization results, the optimum parameter combination was identified as:

- Polishing Grit Size = 1200 grit
- Oxidation Time = 30 min
- Oxidation Temperature = 380°C

A confirmation experiment conducted under these conditions produced a surface roughness value of approximately 0.12 μm, which corresponds to the minimum roughness obtained among all experimental runs. The close agreement between the predicted and experimental values confirms the adequacy and reliability of the Taguchi optimization methodology for predicting surface roughness in QPQ-treated EN8 steel.

The experimental investigation demonstrates that polishing grit size is the dominant factor controlling the surface roughness of QPQ-treated EN8 steel. Increasing the polishing grit size from 800 to 1200 reduced the average roughness from 0.4647 μm to 0.1580 μm, corresponding to an overall reduction of approximately 66%.

The improvement in surface finish is attributed to the efficient removal of the outer asperities and irregularities generated during nitrocarburizing and oxidation. Finer polishing produces a smoother surface morphology, thereby reducing surface defects and improving tribological performance.

Although oxidation temperature and oxidation time exerted comparatively smaller influences on roughness, they remain important for the formation of the protective Fe_3O_4 oxide layer responsible for enhanced corrosion resistance. Excessive oxidation temperature and prolonged oxidation duration slightly increased surface roughness due to additional oxide growth and surface layer thickening.

The optimized condition of 1200 grit polishing, 30 min oxidation time, and 380°C oxidation temperature produced the smoothest surface and is expected to enhance wear resistance, corrosion resistance, and fatigue performance of EN8 steel piston rods employed in gas spring applications.

The present findings are in good agreement with previous investigations on QPQ-treated steels, which reported that optimized polishing and controlled oxidation significantly improve surface integrity, tribological behavior, and corrosion resistance [1], [20]

5. Conclusion

This study investigated the effects of polishing grit size, oxidation time, and oxidation temperature on the surface roughness of QPQ salt bath nitrided EN8 steel using a Taguchi L9 orthogonal array. The results demonstrated that the surface roughness of QPQ-treated EN8 steel is strongly influenced by the selected finishing parameters, with measured roughness values ranging from **0.12 μm to 0.48 μm**.

Among the investigated factors, **polishing grit size** was identified as the most significant parameter affecting surface finish. Increasing the polishing grit size from **800 to 1200 grit** reduced the average surface roughness from **0.4647 μm to 0.1580 μm**, corresponding to an improvement of approximately **66%.** Signal-to-Noise ratio analysis and ANOVA confirmed that polishing grit size was the dominant factor, contributing approximately **95.5%** of the total variation in surface roughness, whereas oxidation time and oxidation temperature had comparatively minor effects.

Taguchi optimization identified the optimum process parameters as **1200 grit polishing, 30 min oxidation time, and 380°C oxidation temperature**, which produced the minimum surface roughness of approximately **0.12 μm.** The confirmation experiment validated the predicted optimum condition and demonstrated the reliability of the optimization approach.

A regression model developed for surface roughness prediction exhibited a high coefficient of determination (**R^2 = 97.43%**), indicating excellent agreement between experimental and predicted values. The optimized QPQ treatment parameters are expected to improve the tribological performance, corrosion resistance, sealing effectiveness, and service life of EN8 steel gas spring piston rods.

Overall, the study confirms that optimization of polishing and post-oxidation conditions is essential for achieving superior surface quality in QPQ-treated EN8 steel and provides useful guidelines for industrial surface engineering applications.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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