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Optimization of Burnishing process by Taguchi method for surface enhancement of EN31 steel

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Abstract

Surface finish plays important role in service characteristics of an element, such as corrosion resistance, wear resistance and fatigue life. This leads to investigate surface finishing processes like polishing, buffing, lapping, burnishing etc. Burnishing is well known, effective and efficient super finishing technique which involves surface layers plastic deformation by cold working to refine surface texture and improve service life of component. Current work focuses on investigation of ball burnishing process and optimization of it on EN31 steel. Taguchi method is implemented for determination of best possible process parameters combination to decrease surface roughness and increase hardness of EN31 steel specimens. After burnishing surface roughness decreases from 0.446 to 0.089 μm and hardness increases from 179.5 to 266.5 Hv. Burnishing speed and feed are remarkable factors for decreasing surface roughness, whereas no. of tool passes and applied force are crucial for increasing hardness, according to optimization results. Validation tests are carried out with ideal levels of process parameters, confirming that the process of ball burnishing has improved the surface finish and hardness of EN31 steel.

1. Introduction

Carbon alloy (EN31) steel is a promising material of the automotive sector, and attaining dimensional precision with excellent surface qualities when machining this alloy is a difficult task; after machining process, it require surface finishing process. Gauges, ball and roller bearings, taps, drill bit, ejector pins, swaging dies are all popular examples for EN31 steel. It is a high-quality steel that is suitable for wear-resistant machine components and press tools [1]. Surface characteristics are amongst the most significant aspects of machine components, since they have a direct impact on their overall performance and economics of manufacture. Surface improvement and dimensional precision are nowadays more important in the manufacturing firm. Though polishing, honing, buffing, grinding, and lapping are traditional surface treatment techniques used to improve product quality they require a trained operator to execute. To solve these problems, ball burnishing is used which is chip less, low-cost finishing technique that requires less processing time for greater surface quality [2, 3]. A hard roller or ball is used in burnishing to deform the material plastically as it moves over a surface of the workpiece to generate compressive residual stresses and enhance surface hardness [4].

Ball burnishing enhances surface roughness by plastic deformation with minimal material loss. It is applied after machining to enhance materials surface texture [5]. Surface hardness increases and surface roughness decreases as a result of this procedure. It also involves the growth of tensile strength and corrosion resistance, as well as the generation of residual stresses required for deformation of surface [6, 7]. Many studies have looked at the impact of process variables such as type of burnishing tool, diameter and material of ball, applied force, lubricants used, feed, speed and no. of tool passes on integrity of surface [8].

Many investigators are signalized that surface roughness and hardness of complex geometry parts are improved by burnishing. The ball burnishing technique is used to enhance the surface quality of previously machined workpieces. The burnishing technique is applied to workpieces made of aluminium materials with convex or concave surfaces. After experimentation final results are compared with those results obtained prior to burnishing. Findings show that improvement of surface roughness imparted due to the ball burnishing method [9]. On contoured surfaces, ball burnishing is used to improve surface roughness. Burnishing has two methods: continuous burnishing and patch burnishing. Complex components can be burnished using both processes, resulting in a significant increase in surface roughness. Experimentally, two alternative geometries of AISI 1045 and DIN 1.2379 steel components are employed, each having differing properties. One having hemisphere shaped simple geometry and the other having more complex geometry. Both methods of burnishing were assessed for surface quality, with substantial improvements in surface roughness and hardness [10]. CFRP has been widely employed in the industry because of its robustness, reliability, simplicity, corrosion resistance qualities than traditional metals. It is important to produce CFRP components with high precise surface quality for applications such as automobile, aerospace, and biomedical instruments. Further surface modification procedures are thus required for CFRP processing following machining to suppress inferior surface quality. The ball burnishing will provide the effective solution to achieve superior surface quality [11].

Burnishing has been studied extensively to see how it affects steel materials surface characteristics. Burnishing process energy efficiency is rarely taken into account because it required significant work. With optimizing input component, the power factor, average roughness and BHN may all be improved at the same time, while demand of energy for the burnishing process of SKD61 steel is reduced. The operating variables included the burnishing feed, speed and penetration depth [12]. D2 is common steel in the manufacturing sector because it is conventional. D2's wear resistance may be improved using techniques like shot peening and nitriding. Burnishing's impact on D2 steel's surface quality has been thoroughly investigated [13]. A carbide burnishing tool provides superior product quality and user-friendly machining features on AISI-1040 high carbon steel [14]. To achieve a maximum fatigue life, essential parts like compressor, pump parts and turbines, must be machined to create compressive residual stress on the surface layer. Burnishing has indeed been extensively employed in industry as an efficient way of generating and improving the compressive residual stress of machined components [15]. Enhancing the surface properties of AISI 1045 steel using roller burnishing procedures is among the most efficient ways to save machining time and cost [16]. Because of its improved corrosion resistance, chromium–nickel steel AISI 316Ti is most often utilised in different sectors of engineering. The slide burnishing process substantially enhances the surface characteristics of chromium–nickel steel [17]. Surface integrity of AISI 4140 steel is improved by a coupled machining process known as Combined Turning-Burnishing (CoTuB) [18].

With a TiAlN coated tungsten carbide roller, burnishing eliminates the requirement for super finishing process following the traditional turning process to improve the surface finish of Al(B4C)p Metal Matrix Composites [19]. LPB induces deep layer of residual stress that improves fatigue and corrosion fatigue performance of friction steer welded aluminum alloy [20]. Maximum tension ranged in friction steer welded AA2219 plate is from 100 MPa at the surface to 200 MPa at mid-thickness. LPB is applied in the weld region in high compression on the order of 400 MPa. After LPB there is reduction of the pitting corrosion damage, with fatigue life improvement. LPB seems to be a feasible post weld treatment for improved corrosion and fatigue performance of aluminum alloy [21]. LPB provide a deep stable surface layer of high magnitude compression with controlled, low cold working normally in the 3%–5% range in titanium, aluminium and nickel based alloys and steels and with improved surface roughness [22]. LPB is now used for manufacturing of several aerospace, medical, nuclear applications including military turbine engine blades and the propeller taper bore for the P-3 Orion [23]. Some studies also reveals that cryogenic treatment of cutting tool improves surface finish of AISI 304 stainless steel and 1.2343 tool steel significantly [24–26]. MQL having its effect on surface roughness of AISI D2 steel [27]. Moreover, as observed from the literature, there haven't been many researches on the burnishing of carbon alloy steel (EN31).

For the present experimentation, unique ball burnishing tool is developed. The L25 orthogonal array of Taguchi optimization approach was used to examine the influence of process variables like burnishing speed, burnishing feed, burnishing force, and no. of passes on surface roughness and hardness in this paper.

Taguchi approach has resulted in a novel and strong optimization methodology that varies from traditional methods [28, 29]. This approach can successfully and inexpensively solve issue related to design optimization and problem solving with smaller no. of tests without building process model. As a result, the Taguchi technique minimises the time and expense involved in experimental studies while also improving performance qualities. ANOVA i.e. analysis of variance is used to find out the relevance of the burnishing process factors and an ANOM i.e. analysis of means is used to find out the ideal values.

1.1. Objectives

This article investigates process parameters effect on surface roughness and hardness after ball burnishing of EN31 steel samples in depth. This investigation's goals may be divided into four categories.

- Begin by optimising the speed in order to minimise surface roughness and improve surface hardness.
- To minimise surface roughness and obtain a superior surface hardness by optimising the feed at an optimal speed.
- To decrease surface roughness and achieve a good surface hardness by optimising the burnishing force at an optimal speed and feed.
- To determine the ideal number of passes, speed, feed, and burnishing force for achieving excellent surface integrity.

2. Materials and methods

2.1. Methodology

The Taguchi technique reduces the number of tests required to identify the best and most reliable process parameter combinations. Users benefit from this method since it saves time and cost. This approach is one of the most straightforward and efficient ways to improve the design of high-quality, cost effective systems. The factorial design selection is a critical step that aids in the execution of tests to determine the process parameters optimal level. It has the advantage of arranging burnishing sequences with no duplicates. Taguchi's technique having three approaches that describes the relationship between variability and qualification. Frequently used three approaches are 'Smaller the better', 'Larger the better', and 'Nominal the better'. To attain the ideal performance outcome of the factors in present investigation, 'Smaller the better' approach was favoured for determining the S/N ratio for surface roughness, and 'Larger the better' approach was favoured for calculating the S/N ratio for hardness, and it is determined by below mentioned equations (1) and (2), respectively.

$$nij = -10\log_{10}\left(\frac{1}{n}\sum_{j=1}^{n} y_{ij}^{2}\right) \quad (1)$$

$$nij = -10\log_{10}\left(\frac{1}{n}\sum_{j=1}^{n} \frac{1}{y_{ij}^{2}}\right) \quad (2)$$

Where yij represents the *i*th trial at the *j*th test, n represents the total no. of trials/readings for the given (*j*th) answer, and s represents the standard deviation.

Following methodology is used in present study:

- The process parameters to be used and the performance characteristics to be defined are chosen.
- The number of process parameters and levels determines which factorial design is used.
- Tests were conducted by using chosen factorial design.
- The S/N ratio is computed.

Table 1. Chemical composition of EN31 steel.

Element	C	Si	Mn	P	S	Cr
Wt. (%)	0.95	0.30	0.45	0.040	0.040	1.40

- S/N ratio and ANOVA are employed to evaluate test findings.
- Best process parameters are identified.

The degree of freedom was computed as '24' in this investigation, which employed five distinct levels of four different process parameters. The degree of freedom in experimentation must be equal to or lower than the process parameters for the accurate selection of the orthogonal array. Table 2 shows the considered process parameters with corresponding values. In comparison to a complete factorial based experiment design, the number of experiments has been reduced because of usage of the Taguchi method, which enabled authors to save time and cost. The S/N ratio was determined for each experiment in order to analyse the data (table 4).

2.2 Experimental work

2.2.1. Material

The purpose of this study was to see how burnishing parameters affect surface roughness and hardness of EN31 work material. In the current work, optical emission spectroscopy is employed to evaluate alloy's chemical composition. Table 1 shows the chemical composition of carbon alloy EN31 steel. For the experiments, extruded round bar was selected with dimensions as 15 mm in diameter and 100 mm in length.

2.2.2. Burnishing

Burnishing can be performed after completion of turning on lathe. A newly designed burnishing tool uses spring force to pressurise the ball, and it may be fitted to either a conventional or CNC lathe, as illustrated in figure 1 (b). A 10 mm diameter tungusten carbide ball is used in burnishing tool. A standard lathe (Kirloskar make, model: Turnmaster 40) was utilised in this study to show the technology's simplicity and possible industrial applications.

2.2.3. Experimental procedure

Based on preliminary study, four process variables are evaluated in current investigation: burnishing speed, feed, force, and no. of passes. To investigate nonlinearity impacts, each process variable was evaluated at five levels. Table 2 shows the chosen process variables and respective levels.

The Taguchi technique is used to choose an L25 OA with four columns and twenty-five rows; each process variable is allocated to a column, and twenty-five

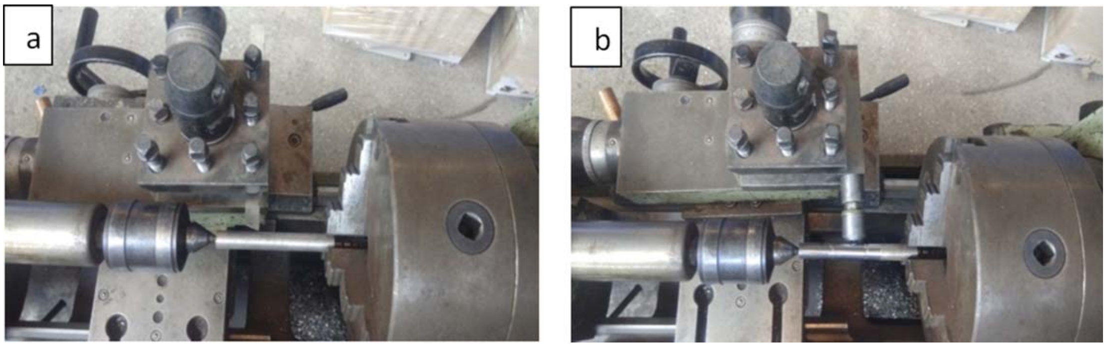

Figure 1. Turning process on lathe (a) and burnishing process on same lathe by keeping work piece setting as it is (b).

Table 2. Process variables and their levels.

Process variables	Code	Unit	Levels 1	2	3	4	5
Burnishing Speed (v)	A	m min^{-1}	13.2	18.8	29.7	47.1	75.4
Burnishing Feed (f)	B	mm rev^{-1}	0.045	0.071	0.112	0.18	0.28
Burnishing Force (F)	C	Kg	10	25	40	55	70
No. of passes (N)	D	—	1	2	3	4	5

Table 3. Orthogonal array, variables level and respective S/N ratios of measured responses.

	Process variables				Results			
Exp.	Speed (m min^{-1})	Feed (mm rev^{-1})	Force (Kg)	No. of passes (N)	Surface roughness, Ra (μm)	S/N ratio for surface roughness	Hardness, H (Hv)	S/N ratio for hardness
1	13.2	0.045	10	1	0.120	18.4164	228.00	47.1587
2	13.2	0.071	25	2	0.153	16.3062	234.50	47.4029
3	13.2	0.112	40	3	0.191	14.3793	247.50	47.8715
4	13.2	0.18	55	4	0.210	13.5556	251.00	47.9935
5	13.2	0.28	70	5	0.339	9.3960	253.00	48.0624
6	18.8	0.045	25	3	0.110	19.1721	220.50	46.8682
7	18.8	0.071	40	4	0.205	13.7649	253.00	48.0624
8	18.8	0.112	55	5	0.296	10.5742	261.50	48.3494
9	18.8	0.18	70	1	0.194	14.2440	245.50	47.8010
10	18.8	0.28	10	2	0.303	10.3711	223.00	46.9661
11	29.7	0.045	40	5	0.129	17.7882	251.00	47.9935
12	29.7	0.071	55	1	0.168	15.4938	248.00	47.8890
13	29.7	0.112	70	2	0.157	16.0820	252.50	48.0452
14	29.7	0.18	10	3	0.111	19.0935	210.50	46.4650
15	29.7	0.28	25	4	0.185	14.6566	235.50	47.4398
16	47.1	0.045	55	2	0.196	14.1549	239.00	47.5680
17	47.1	0.071	70	3	0.273	11.2767	245.50	47.8010
18	47.1	0.112	10	4	0.205	13.7649	229.50	47.2157
19	47.1	0.18	25	5	0.289	10.7820	236.50	47.4766
20	47.1	0.28	40	1	0.338	9.4217	211.00	46.4856
21	75.4	0.045	70	4	0.176	15.0897	252.50	48.0452
22	75.4	0.071	10	5	0.386	8.2683	230.50	47.2534
23	75.4	0.112	25	1	0.199	14.0229	223.00	46.9661
24	75.4	0.18	40	2	0.201	13.9361	217.50	46.7492
25	75.4	0.28	55	3	0.294	10.6331	249.50	47.9414

unique factor combinations are available. Hence, twenty-five tests are sufficient to analyse the whole burnishing experimental design space when employing the L25 OA. Table 3 shows experimental design that was employed in current investigation. The average value of roughness before burning was 0.446 μm, and the hardness was 179.5 Hv. Kerosene is used as lubricant in the current study.

Table 4. Surface Roughness ANOM.

Parameter code	Levels					Optimal	
	1	2	3	4	5	Values	Level
A	14.4107	13.6253	16.6228	11.8801	12.3900	16.6228	3
B	16.9243	13.0220	13.7647	14.3222	10.8957	16.9243	1
C	13.9828	14.9880	13.8580	12.8823	13.2177	14.9880	2
D	14.3198	14.1701	14.9110	14.1664	11.3617	14.9110	3

Table 5. Hardness ANOM.

Parameter code	Levels					Optimal	
	1	2	3	4	5	Values	Level
A	47.6978	47.6094	47.5665	47.3094	47.3911	47.6978	1
B	47.5267	47.6817	47.6896	47.2971	47.3791	47.6896	3
C	47.0118	47.2307	47.4324	47.9483	47.9510	47.9510	5
D	47.2601	47.3463	47.3894	47.7513	47.8271	47.8271	5

Table 6. Surface Roughness ANOVA.

Parameter code	Degree of freedom	Sum of square	Mean square	F value	P value	% contribution
A	4	70.23	17.556	12.62	0.002	30.74
B	4	95.37	23.843	17.13	0.001	41.74
C	4	13.14	3.285	2.36	0.140	5.75
D	4	38.60	9.650	6.93	0.010	16.90
Error	8	11.13	1.392	—	—	4.87
Total	24	228.47	—	—	—	100

To maintain the turning alignment and avoid the out of roundness problem, the burnishing operation was performed after turning without unclamping the workpiece. (figure 1). The surface roughness was assessed to check the superiority of the treated surface caused by the burnishing process, and the hardness parameter was utilised to describe the influence of specific process variable. The surface roughness of pre-burnished and post-burnished surfaces was determined using the surface roughness tester: Surf test model SJ-210' (Mitutoyomake). Process response was recorded with 0.8 mm cut-off length for measurements of surface roughness. The hardness of sample was determined using Vickers hardness tester (Model 'SM5'). Surface morphology of turned and burnished surfaces of sample was captured by using scanning electron microscope (SEM) (Model 'Joel JSM-IT200 LV').

3. Results and discussion

3.1. Analysis of means and analysis of variance

Objective of this study is to see how burnishing factors affect surface roughness (Ra) and hardness (H), as well as to reduce surface roughness and optimise hardness by ball burnishing. Surface roughness has been assigned to the 'smaller the better' category, whereas hardness has been assigned to the 'larger the better' category. Equations (1) and (2) were used to calculate the corresponding S/N ratios for every test of the OA. Table 3 shows the respective S/N ratios for every test of the L25 orthogonal array.

The ideal levels of process variables were determined using an ANOM i.e. analysis of means depending on the S/N ratio. Tables 4 and 5 show the findings of analysis of means.

The optimum combination level is the level of a variable having maximum S/N ratio. For minimal surface roughness, the best parameter settings are A3, B1, C2 and D3, whereas for maximum hardness, the ideal parameter settings are A1, B3, C5 and D5. Depending on the S/N ratio, the ANOVA i.e. analysis of variance was implemented to evaluate the impacts of burnishing process variables statistically [29]. Table 6 summarises the surface roughness results of ANOVA.

The Analysis of variance tables reveal that for reducing surface roughness burnishing speed (30.74%) and burnishing feed (41.74%) play a vital role , but burnishing force (5.75%) and number of passes (16.90%) have little influence on surface roughness.

Likewise, ANOVA findings of hardness are summarised In table 7.

Burnishing force (51.30%) and no. of tool passes (18.73%) are key variables in optimising hardness, but burnishing speed (7.32%) and burnishing feed

Table 7. Hardness ANOVA.

Parameter code	Degree of freedom	Sum of square	Mean square	F value	P value	% contribution
A	4	0.5131	0.1283	1.06	0.434	7.32
B	4	0.6219	0.1555	1.29	0.351	8.88
C	4	3.5933	0.8983	7.45	0.008	51.30
D	4	1.3122	0.3281	2.72	0.106	18.73
Error	8	0.9645	0.1206	—	—	13.77
Total	24	7.005	—	—	—	100

Table 8. Validation tests results.

Performance measure	Surface roughness	Hardness
Factor Levels	$A_3B_1C_2D_3$	$A_1B_3C_5D_5$
S/N Predicted(ηopt)dB	22.0887	48.6209
Observed value	0.089	266.5
S/N observed(ηobs)dB	21.0122	48.5139
Prediction error, dB	1.0685	0.107
Confidence interval value (CI), dB	±3.35569	±0.98772

(8.88%) have no apparent influence on hardness, as shown in the ANOVA tables.

By using equation (3) η_{opt} i.e. predicted S/N ratio is calculated [28]:

$$\eta_{opt} = m + \sum_{j=1}^{p} [(m_{i,j})_{\max} - m] \quad (3)$$

Where m is the total mean of S/N ratio, $(m_{i,j})_{max}$ is the S/N ratio of the best combination level i of factor j and p is number of main design factor. The sample calculation of η_{opt} for surface roughness is as follow:

$$\eta_{opt} = 13.7858[(16.6228 - 13.7858) + (16.9243 - 13.7858) + (14.9880 - 13.7858) + (14.9110 - 13.7858)]$$

$$\eta_{opt} = 13.7858 + 8.3029 = 22.0887$$

The confidence interval (CI) is obtained by calculating the closeness between the observed S/N ratio (η_{obs}) and the predicted value (η_{opt}), Calculated by [28]:

$$CI = \sqrt{F_{(1,v_e)} V_e \left(\frac{1}{\eta_{eff}} + \frac{1}{\eta_{ver}} \right)} \quad (4)$$

Where $F_{(1,v_e)}$ is the F value for 95% CI, v_e is the degrees of freedom for error, V_e is the variance of error, $\eta_{eff} = \frac{N}{1+v}$; N = Total No. of trials in OA and v = degrees of freedom of p factors and η_{ver} is the validation test trial number.

$$\eta_{eff} = \frac{N}{1+v} = \frac{25}{1+4+4+4+4} = 1.4706$$

For validation 20 samples are produced

$$\eta_{ver} = 20; F_{(1,v_e)0.95} = 5.32 \quad and \quad V_e = 1.392$$

$$CI = \pm\sqrt{5.32 \times 1.392\left(\frac{1}{1.4706} + \frac{1}{20}\right)}$$

$$= \pm 3.35569$$

The workpieces of similar lots were manufactured at the ideal values of the process variables. Observed (η_{obs}) and predicted (η_{opt}) values of S/N ratio are compared. Table 8 summarizes validation tests output. It demonstrates that the prediction error (ηopt–ηobs), is within the confidence interval (CI) value, showing that the surface roughness model and hardness model are acceptable.

Table 9 shows the best process variable combinations for optimum surface roughness and hardness, as well as their respective optimum values.

3.2. Burnishing parameters effects analysis

To investigate how process variables of ball burnishing affect surface roughness and hardness the direct effect plots are originated.

3.2.1. Surface roughness analysis

The change in pre-burnished and post-burnished surface roughness of workpiece portion is shown in figure 2. The machining traces on turned surfaces are clearly visible on left side and glossy region on right side shows a finer burnished surface.

Pre-burnished and post-burnished surface profiles are shown in figure 3. The original surface roughness after turning was 0.446 μm, however it was decreased to 0.089 μm after burnishing. By seeing topography (figure 3) one can easily interpret that burnishing procedure results in a considerable decrease in surface roughness. Moreover it can be seen from figure 3 that burnishing flattened surface crests and makes workpiece surface smoother.

Surface roughness increases as the burnishing speed is raised from 13.2 to 18.8 m min^{-1}, but it decreases when the speed is raised to 29.7 m min^{-1}, as seen in the surface roughness direct effect plot (figure 4). There is increment in surface roughness as the burnishing speed rises from 29.7 to 47.1 m min^{-1}. When burnishing speed is high, the temperature of the burnishing ball and the specimen rises due to the burnishing tool's inability to pass over the specimen's surface, resulting in an incremental material variation in between specimen and the ball coherence, as a result, better surface roughness [9, 10]. The ball gets

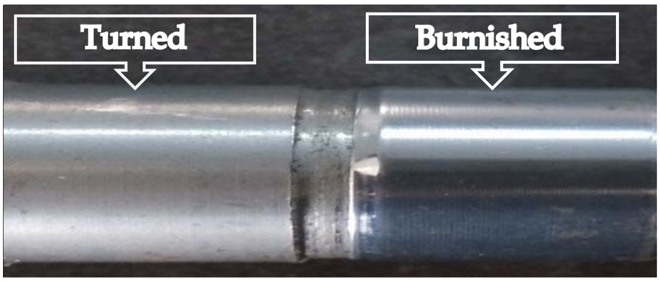

Figure 2. Image of turned and burnished side after turning.

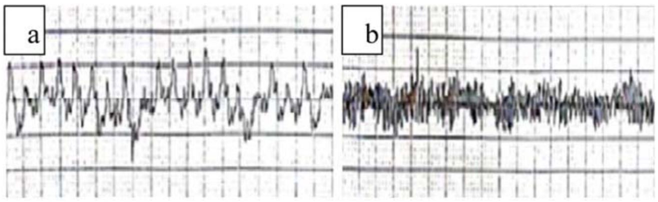

Figure 3. (a) Turned surface profile (b) burnished surface profile.

Table 9. Ideal process variable setting and respective best values combination for surface roughness and hardness.

	Ideal process variable setting				
Response	Burnishing speed (m mm^{-1})	Burnishing feed (mm rev^{-1})	Burnishing force (Kg)	Number of passes (N)	Optimal value
Surface roughness	29.7	0.045	25	3	0.089 μm
Hardness	13.2	0.112	70	5	266.5Hv

more time to stabilize the imperfections when the burnishing speed is medium, and therefore the surface roughness is reduced. Furthermore, the burnishing tool has less deformation time to smooth out additional imperfections at higher speeds, and there is an increment in surface roughness owing to chatter [5, 11].

Figure 4 demonstrates that at decreased feed rates (0.045 mm rev^{-1}) burnishing ball gets more opportunities to flatten the protruding outlines of the former footprints since the tool is moving sluggishly. Surface roughness is reduced as a result. Surface roughness rises dramatically at elevated feed rates, i.e. 0.071–0.28 mm rev^{-1}. Burnishing ball footprints are spaced more apart as the feed rate increases, which reduces the ability of the previous footprints to flatten down their protruded edges, thereby increasing surface roughness. Burnishing ball with a middle distance between two successive indentations also produces bigger feed marks at greater feed rates, resulting in increased surface roughness [8]. Due to burnishing tools stronger distortion effect and uniform material circulation at lesser feed, lesser feeds are superior for improved surface roughness, as seen in figure 4.

The surface roughness reduces significantly for forces between 10 and 25 kg, and rises for forces between 25 and 70 kg as shown in figure 4. A small amount of flaws are deformed by the burnishing ball, which causes a reduction in surface roughness. Increasing the force causes the work profile in front of the burnishing tool to expand, leading to an increase in surface roughness [23]. The plastic distortion operation repeated on work surface causes higher work-hardening of the previous inflated layers of the distorted surface. Accelerates grain production and an increase in surface roughness are outcomes of the increased work-hardening action. It is recorded that elevated force reduces surface roughness by increasing ball pressure on the workpiece, which condenses most imperfections and increases metal flow, resulting in fattened hills and more filled-in gaps or valleys in the subsurface layer.

Surface roughness reduces as no. of tool passes increases, it achieves a minimal value when the no. of tool passes is set to 3 (figure 4). However, as the no. of tool passes rises, roughness of surface rises dramatically. Over hardening as well as crumbling of surfaces are both possible reasons for why roughness rises with

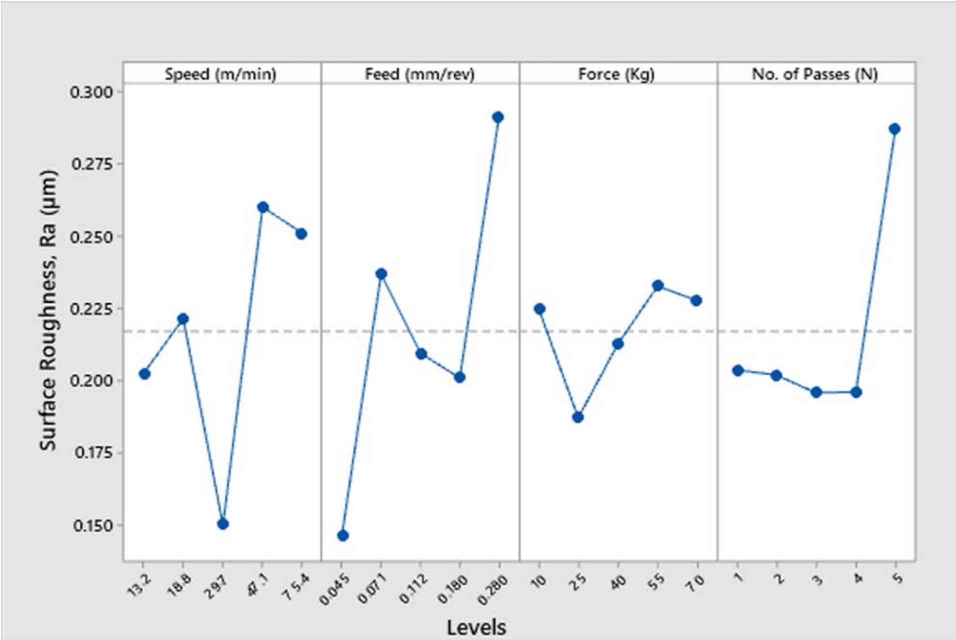

Figure 4. Surface roughness direct effect plots.

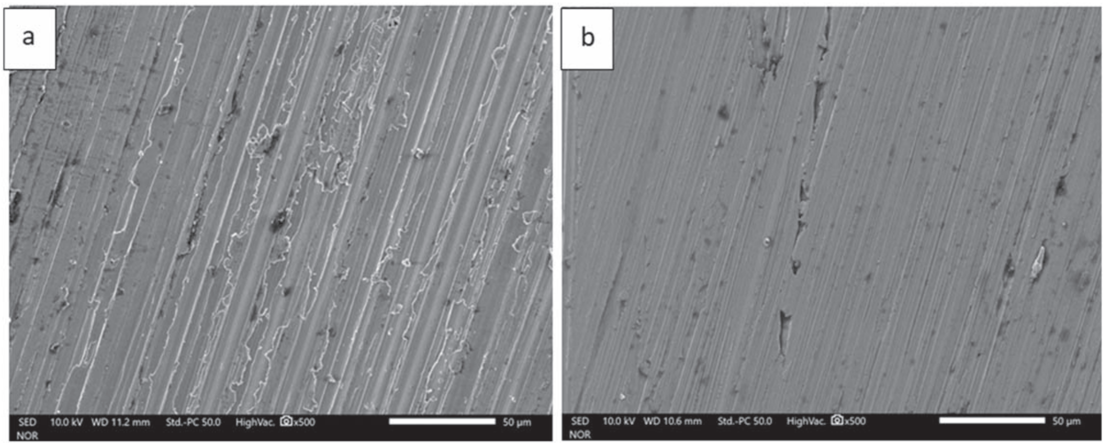

Figure 5. Surface morphology of EN 31 steel (a) pre-burnished (b) post-burnished.

increasing number of passes, which happens because of numerous burnishing on workpiece [11, 28].

Figure 5 shows the surface morphology of EN31 steel before burnishing and after burnishing. The turned surface of workpiece shows traces of significant roughness in comparison to burnished surface, as seen in figure 5.

3.2.2. Hardness analysis

Burnishing parameters effect on hardness are presented in direct effect plots (figure 6). Hardness reduces when burnishing speed (13.2–47.1 m s^{-1}) increases throughout the first range. A higher burnishing speed leads to a higher rate of surface deformation owing to the rise in work-hardening recovery on a surface because of increased temperature of workpiece and burnishing ball. At elevated speed burnishing tool is also unstable across the workpiece surface, resulting in a fragmented deforming effect of the tool, which reduces hardness. It was found that the burnishing was insufficient, especially at higher speeds, and the hardness may be poor as a result. An increase in hardness was shown to be more effective when burnishing at a speed of 13.2 m s^{-1}. A feed rate of 0.045–0.112 mm rev^{-1} leads to an increase in hardness. With an increase in feed (0.112–0.28 mm rev^{-1}), the hardness falls steadily. At reduced feed rates, plastic deformation is more severe, resulting in a higher rise in hardness. The no. of times a ball passes on identical area is larger at lower feed than at higher feed, too [1, 4].

When the feed is increased, the burnished surface's work hardening effect reduces, and it increases as feed is reduced. When the feed rate is increased, the

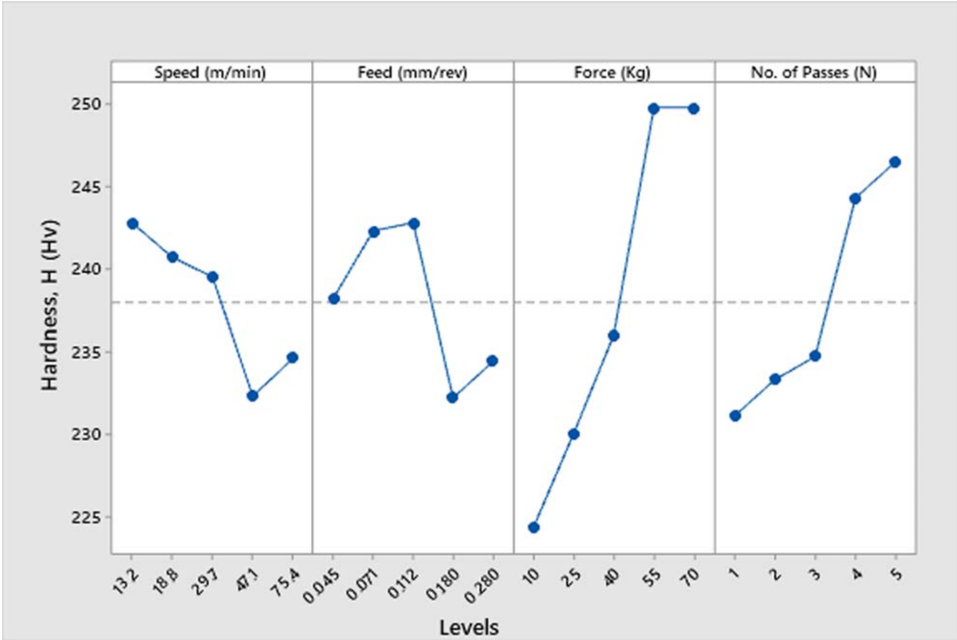

Figure 6. Hardness direct effect plots.

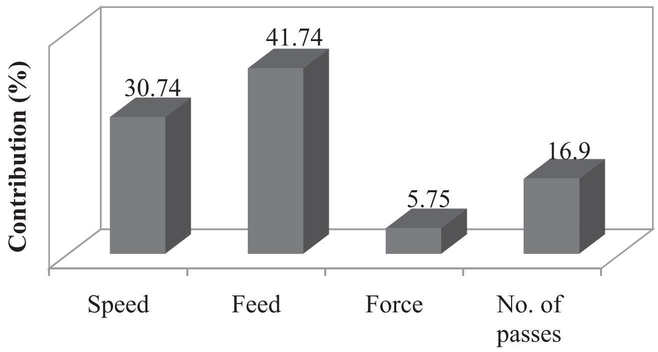

Figure 7. Process variables percentage contribution on surface roughness.

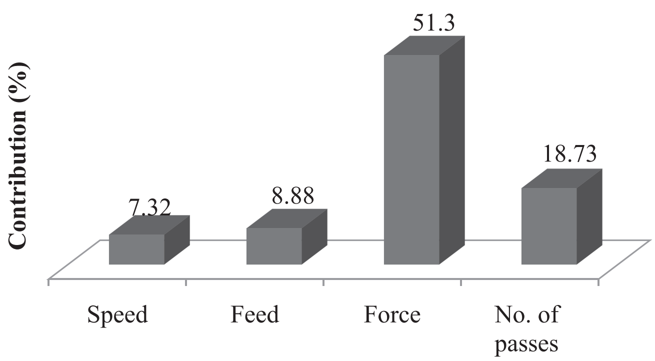

Figure 8. Process variables percentage contribution on hardness.

hardness decreases due to little work-hardening occurring on surface because lower surface area being exposed to plastic distortion. On the other hand, the change in burnishing force from 10 to 70 kg indicates that, the hardness progressively increases because both work hardening and surface deformation are increased. Outcomes (figure 6) demonstrate that as the no. of tool passes rises, hardness improves leading to a more compact grain structure with greater structural uniformity [5]. The hardness ranged from 210.5 Hv to 261.5 Hv in the present burnishing trials. Prior to burnishing, the EN31 work piece material had a hardness of 179.5 Hv. In the process of burnishing, a material's surface and adjacent subsurface becomes harder as a response of work hardening, which is caused by thermo - mechanical forces on work piece [8, 11, 15].

Plastic deformation occurs when material is continuously moved across a surface, resulting in work hardening and a harder surface. When the surface is burnished, the hardness of the surface is significantly greater than that of the material's core hardness. As a result of work hardening, the upper part of the burnished surface is harder than that of the pre-burnished surface. It is important to note that the material underneath is more softer because EN31 steel has been over aged due to the high cutting temperatures generated there at adjacent surface. All of the above experiments and analysis on hardness after burnishing of EN31 steel suggest that due to effect of work hardening, the work piece material's hardness rises with increasing burnishing force and no. of tool passes [11, 16].

4. Conclusions

To decrease surface roughness and enhance hardness while burnishing with a ball burnishing tool, Taguchi optimization is used in current article. Burnishing speed, burnishing feed, applied force, and no. of tool passes are all scrutinize as control factors. On the basis of the assessment of the experimental data, the following findings may be derived from the current study.

Surface roughness can be decreased by burnishing at a medium speed with a low feed, a small burnishing force and three passes. On the other hand, to increase the surface hardness, burnishing can be done at a low speed, with a medium feed, with a greater force and more no. of passes.

Surface roughness is greatly reduced by the burnishing speed and burnishing feed with respective contributions of 30.74% and 41.74% as shown in figure 7. Burnishing force and no. of passes, which account for 51.30% and 18.73%, have a substantial impact on hardness maximisation as shown in figure 8.

- According to the current studies, surface roughness rises as burnishing feed and force increases. Usually with higher burnishing speed and no. tool of passes, the roughness reduces till it hits the minimum value and it start to rise with additional speed and no. of passes.
- Hardness rises as force and no. of tool passes increase. As speed and feed rise, the hardness of the work piece increases, but only in defined low limits, and it start to decrease at higher limits.
- When compared with the pre-burnished work piece, Taguchi optimization revealed higher enhancements in surface finish (80%) and noticeable enhancements in hardness (32%).

The burnishing process is a new technique that has a lot of advantages from industrial point of view. As a result, more work may be done with the models for burnishing to increase the corrosion resistance after burnishing.

Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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References

[1] Ravindra Babu P, Ankamma K, Siva Prasad T, Raju A V S and Eswara Prasad N 2011 Effects of burnishing parameters on the surface characteristics, microstructure and microhardness in EN series steels *Trans. Indian Inst. Met.* **64** 565–73
[2] Hegab H, Umer U, Soliman M and Kishawy H A 2018 Effects of nano-cutting fluids on tool performance and chip morphology during machining inconel 718 *Int. J. Adv. Manuf. Technol.* **96** 3449–58
[3] Varpe N J, Hamilton A and Gurnani U 2021 Review of effect of burnishing process on surface integrity of friction stir welded components *Des. Eng.* **2021** 651–66
[4] Yuan X, Sun Y, Li C and Liu W 2017 Experimental investigation into the effect of low plasticity burnishing parameters on the surface integrity of TA2 *Int. J. Adv. Manuf. Technol.* **88** 1089–99
[5] Revankar G D, Shetty R, Rao S S and Gaitonde V N 2017 Wear resistance enhancement of titanium alloy (Ti–6al–4v) by ball burnishing process *J. Mater. Res. Tech.* **6** 13–32
[6] Kovalchenko A, Erdemir A, Ajayi O and Etsion I 2017 Tribological behavior of oil-lubricated laser textured steel surfaces in conformal flat and non-conformal contacts *Mater. Perform. Char.* **6** 1–23
[7] Khorasani A and Yazdi M-R-S 2017 Development of a dynamic surface roughness monitoring system based on artificial neural networks (ANN) in milling operation *Int. J. Adv. Manuf. Technol.* **93** 141–51
[8] Banh Q N and Shiou F J 2016 Determination of optimal small ball-burnishing parameters for both surface roughness and superficial hardness improvement of STAVAX *Arab. J. Sci. Eng.* **41** 639–52
[9] Travieso-Rodríguez J A, Dessein G and Gonzalez-Rojas H A 2011 Improving the surface finish of concave and convex surfaces using a ball burnishing process *Mater. Manuf. Process.* **26** 37–41
[10] Lopez De Lacalle L N, Rodriguez A, Lamikiz A, Celaya A and Alberdi R 2011 Five-axis machining and burnishing of complex parts for the improvement of surface roughness *Mater. Manuf. Process.* **26** 997–1003

[11] Suleyman C C, Berat B B and Iskender O 2019 Experimental investigation on the ball burnishing of carbon fiber reinforced polymer *Mater. Manuf. Process.* **34** 1062–7
[12] Nguyen T, Cao L, Dang X and Nguyen T 2019 Multi-objective optimization of the flat burnishing process for energy efficiency and surface characteristics *Mater. Manuf. Process* **34** 1888–901
[13] Toboła D, Brostow W, Czechowski K, Rusek P and Wronska I 2015 Structure and properties of burnished and nitrided AISI D2 tool steel *Mater. Sci.* **21** 511–6
[14] Kumar S, Mitra B and Kumar N 2019 Application of GRA method for multi-objective optimization of roller burnishing process parameters using a carbide tool on high carbon steel (AISI-1040) *Grey. Syst. Theory Appl.* **9** 449–63
[15] He D, Wang B, Zhang J, Liao S and Deng W J 2018 Investigation of interference effects on the burnishing process *Int. J. Adv. Manuf. Technol.* **95** 1–10
[16] Nguyen T and Le X 2018 Optimization of interior roller burnishing process for improving surface quality *Mater. Manuf. Process.* **33** 1233–41
[17] Maximov J T, Duncheva G V, Anchev A P, Ganev N, Amudjev I M and Dunchev V P 2018 Effect of slide burnishing method on the surface integrity of AISI 316Ti chromium—nickel steel *J. Brazilian. Soc Mech. Sci. Eng.* **40** 194
[18] Rami A, Gharbi F, Sghaier S and Hamdi H 2018 Some insights on combined turning-burnishing (Cotub) process on workpiece surface integrity *Int. J. Precis. Eng. Manuf.* **19** 67–78
[19] Shankar E, Prabu S B, Kumar T S and John M R S 2018 Investigation of TiAlN coated roller burnishing on Al-$(B_4C)_p$ MMC workpiece material. *Mater. Manuf. Process.* **33** 1242–9
[20] Hornbach D and Mason P 2002 Improving corrosion fatigue performance of AA2219 friction stir welds with low plasticity burnishing *Int. Surface Engineering Conf.* pp 1–7
[21] Prevéy P and Mahoney M 2003 Improved fatigue performance of friction stir welds with low plasticity burnishing: residual stress design and fatigue performance assessment *Proc. Thermec pp 1–7*
[22] El-Axir M H 2000 Investigation into roller burnishing *Int. J. Mach. Tools Manuf* **40** 1603–17
[23] Sagbas A 2011 Analysis and optimization of surface roughness in the ball burnishing process using response surface methodology and desirability function *Adv. Eng. Softw.* **42** 992–8
[24] Özbek N A 2021 Optimization of flank wear and surface quality in the turning of 1.2343 tool steel using carbide tools coated via different methods *Surf. Topogr.: Metrol. Prop* **9**
[25] Özbek N A, Çİçek A, Gülesİn M and Özbek O 2014 Investigation of the effects of cryogenic treatment applied at different holding times to cemented carbide inserts on tool wear *Int. Journal of Machine Tools and Manuf.* **86** 34–43
[26] Özbek N A, Çİçek A, Gülesİn M and Özbek O 2016 Application of deep cryogenic treatment to uncoated tungsten carbide inserts in the turning of AISI 304 stainless steel *Metallurgical and Materials Transactions* **47** 6270–80
[27] Onur Ö and Saruhan H 2020 The effect of vibration and cutting zone temperature on surface roughness and tool wear in eco-friendly MQL turning of AISI D2 *Journal of Materials Research and Technology* **9** 2762–72
[28] Phadke M S 1989 *Quality Engineering Using Robust Design* (Englewood Cliffs, New Jersey: Prentice-Hall International)
[29] Ross P J 1996 *Taguchi Techniques for Quality Engineering* (New York: McGraw-Hill) 2nd edn