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Original Research

Optimization of turning cutting parameters for casting austenitic stainless steel CF8M used in industrial ball valves

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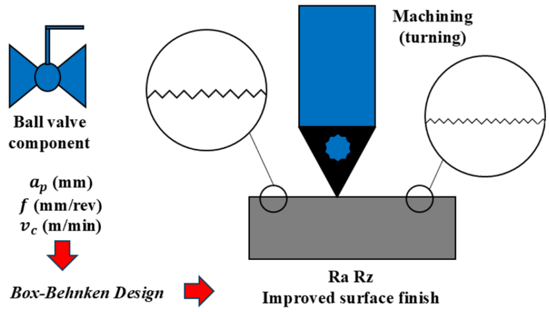


Abstract: Ball valves are widely used in industrial applications due to their high sealing efficiency and operational simplicity. Their performance depends on the contact between a metallic ball and a PTFE sealing element, making the surface finish of the ball critical to ensure tightness and prevent leakage. In this context, this study investigates the optimization of cutting parameters in the turning of ball valve components using the Box–Behnken Design (BBD). Twenty-one balls made of cast austenitic stainless steel ASTM A351 CF8M were machined by varying the depth of cut, feed rate, and cutting speed. Surface roughness was evaluated using a contact profilometer, adopting an average roughness criterion of < 0.4 µm, required to guarantee proper sealing performance. Statistical analysis revealed that the feed rate was the most influential parameter, contributing 77.38% to surface roughness variation. Optimal machining conditions were identified as cutting speed between 200 and 240 m/min, feed rate of 0.08 mm/rev, and depth of cut between 0.3 and 0.5 mm, resulting in values below 0.4 µm. Experimental validation confirmed a significant improvement in surface finish compared to the current process. The proposed optimization provides a practical reference for machining parameter selection in the turning of an austenitic stainless steel valve ball.

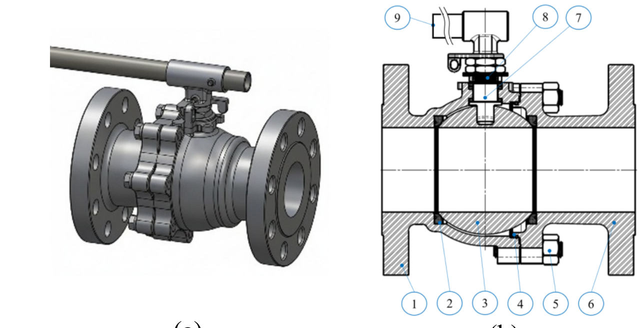
Keywords: Turning machining optimization, cast austenitic stainless steel CF8M, industrial ball valve, surface roughness, Box-Behnken design.

Introduction

Industrial valves are essential devices for controlling and manipulating fluids in industrial processes. They are widely used in various sectors, such as oil and gas, pulp and paper, pharmaceuticals, food, and others. These devices play a fundamental role in both the efficient conduct of the production process and the safety of the installations [1]. Among the various types of valves available, ball valves stand out as the most widely used today. This preference is due to several operational advantages, such as rapid opening (1/4 turn), high sealing capacity, low pressure drop due to the passage diameter being practically equal to that of the piping, and wide versatility in terms of sizes and construction materials [2].

Figures 1 and 2 illustrate the main components and the general operation of a typical floating ball valve. The central component is the spherical obturator (the ball, Figure 1b, item 3), which features a through-hole for fluid passage. Sealing is achieved when the ball's outer surface is pressed against the polymeric seats (e.g., PTFE) during the closed position (Figure 2c). This pressurized metal-polymer contact is primarily responsible for the valve's tightness, preventing fluid leakage even under high pressures [1–3]. Because of this critical dynamic contact, the ball's surface finish directly dictates the equipment's sealing efficiency and operational torque.

The valve ball is commonly manufactured from cast austenitic stainless steel ASTM A351 CF8M, widely used in the manufacture of valve components, pumps, and other equipment intended for handling fluids and environments requiring high corrosion resistance. Chemically, CF8M is equivalent to AISI 316 steel, exhibiting a minimum yield strength of 205 MPa, a minimum tensile strength of 485 MPa, and a minimum elongation of 30% [4].

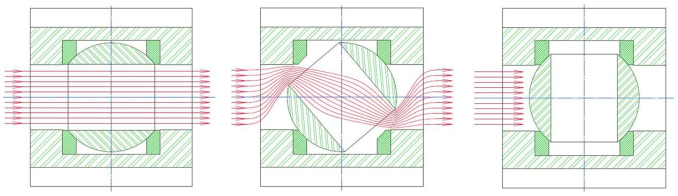


(a) (b)

Figure 1. Floating ball valve, 3-in gauge, and pressure class CL300: (a) 3D drawing; (b) cross-sectional representation.

The ball plays a critical role in the equipment's operation, requiring high dimensional accuracy and low surface roughness levels. To meet these requirements, machining processes such as turning are commonly employed, and in some cases, subsequent grinding and lapping steps, especially in components originating from processes such as casting and forging [5].

Despite the critical role of surface finish in ensuring valve tightness, many manufacturing industries still define machining parameters empirically. This trial-and-error approach often fails to explore the maximum capabilities of the machining processes or to guarantee optimal product quality. Therefore, implementing robust statistical methods, such as the Box-Behnken Design (BBD) combined with Response Surface Methodology (RSM), becomes essential to model the experiments, analyze factor interactions, and optimize the turning process objectively [6, 7].



(a) (b) (c)

Figure 2. (a) Valve in the open position; (b) Valve closing; (c) Valve in the fully closed position.

Thus, in the present study, the cutting parameters currently employed by a valve component manufacturer, specifically in the manufacturing of the valve ball, were initially analyzed. Based on these parameters, expanded variation levels were defined to investigate potential improvements in the machining process. For this purpose, the Box–Behnken Design (BBD) methodology, based on the Response Surface Methodology (RSM), was applied. Statistical analyses and experimental modeling were carried out using Minitab® 22 software. Regarding the application of the BBD methodology for the optimization of machining processes, some recent publications are highlighted and presented below.

Garcia et al. [8] used the Box–Behnken Design (BBD) to optimize machining parameters in the face milling process of duplex stainless steel (DSS). Considered materials with low machinability [9], DSS steels require careful selection of cutting parameters to ensure satisfactory operational results. In their study, it was found that the feed per tooth (f_z) was the factor with the greatest impact on reducing surface roughness. The optimized conditions indicated that the ideal combination for the process consists of low feed per tooth (f_z), low depth of cut (ap), and cutting speed (v_c) at a medium level.

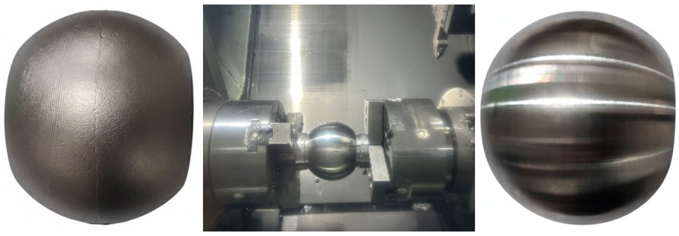
Pinto et al. [10] conducted optimization studies on the turning machining process of super duplex stainless steels (SDSS) using BBD. Their work focused on the stem of a ball valve (Figure 1, item 7), highlighting the importance of low surface roughness levels to reduce friction, minimize wear, and improve the valve's sealing capability against the external environment. In addition to identifying the optimal cutting parameters, analysis of variance (ANOVA) indicated that feed rate was the parameter with the greatest influence on the obtained results.

The Box–Behnken Design (BBD) methodology has proven to be effective in optimizing machining parameters for composite materials, special alloys, and even for the machining of components with hard coatings [10, 11]. However, studies addressing the optimization of machining parameters for valve components are scarce in the literature, particularly with respect to the valve ball. A high-quality surface finish on the ball results in lower friction levels, thereby reducing the forces required for its actuation [12]. In addition, well-finished surfaces contribute to minimizing component wear, increasing equipment service life, and enhancing the fluid sealing capability [13]. In this context, this study proposes the optimization of cutting parameters applied to the turning of a CF8M valve ball. The specific contribution of this research is to establish a systematic, data-driven approach capable of achieving stringent surface finish requirements (Ra < 0.4 μm) directly through the final turning process. By doing so, the study bridges a critical gap in the literature regarding valve component manufacturing and demonstrates the practical feasibility of eliminating subsequent polishing operations. This contribution supports both academic and industrial sectors by promoting reduced manufacturing lead times, lower operational costs, and higher reliability in the production of tight-shutoff ball valves.

Experimental Section

Materials and Methods

The prototypes selected for the experimental tests consisted of twenty-one 3-inch valve balls, with a rough as-cast outer diameter of 121 ± 0.5 mm and a specified post-machining diameter of 118.54 −0.04 +0.01 mm. The balls (samples) were manufactured from cast austenitic stainless steel ASTM A351 CF8M [6] using the investment casting process, as illustrated in Figure 3a. Figure 3b shows a ball secured in the CNC lathe for the finishing turning operation, and Figure 3c presents an example of a ball after the final machining.



(a) (b) (c)

Figure 3. (a) Casting ball; (b) turning of the ball; (c) ball after finishing turning.

Table 1 presents the chemical composition of the sample material according to the relevant standard specifications and laboratory analysis conducted at the company using a Spectromaxx® LMX10 optical emission spectrometer.

Table 1. Chemical composition of ASTM A351 CF8M stainless steel (wt%).

Element	Cr	Ni	Mo	Si	Mn	C	P	S
Measured	19	11	2.5	1.3	1.4	0.04	0.03	0.02
Standard	18 – 21	9 – 12	2 – 3	1.5	1.5	0.08	0.04	0.04

The tool used for the finishing turning operation was a Mitsubishi® TNMG 160408-MJ cemented carbide insert, VP10RT grade, with an AlTiN coating applied by Physical Vapor Deposition (PVD). Initially, five inserts were used, labeled A, B, C, D, and E; for each insert, three cutting edges were utilized, identified as 1, 2, and 3. Thus, a new cutting edge was used for each machined prototype. The machining operations were performed on a ROMI® GL350B CNC lathe, using a synthetic flood coolant with silver nanoparticles (Bondmann® WAY 45–X), diluted in water at a ratio of 1:20. The experimental design using the Box–Behnken Design (BBD), based on Response Surface Methodology (RSM), was conducted with the assistance of Minitab® 22 software. Table 2 presents the machining parameters considered as input

Table 2. Machining parameter levels for the Box–Behnken Design (BBD).

Input factors (controllable)		Levels Lower (-1)	Center (0)	Upper (+1)
Cutting speed	v_c (m/min)	200	220	240
Depth of cut	ap (mm)	0.3	0.5	0.7
Feed	f(mm/rev)	0.08	0.11	0.14

(controllable) factors. The central level (0) corresponds to the values currently employed in the manufacturing of the valve ball, and based on these, upper (+1) and lower (−1) variation levels were defined, according to the limits recommended by the tool manufacturer, aiming to investigate potential improvements.

The BBD allowed the combination and randomization of 15 machining conditions, as shown in Table 3, to optimize the response variables, represented by R_a (average roughness) and R_z (mean peak-to-valley height) values. It is noteworthy that R_a represents a general average (less sensitive to isolated irregularities), while R_z reflects the most extreme peaks and valleys of the roughness profile (more affected by surface irregularities). Therefore, the combination of these parameters can provide a more comprehensive representation of the surface characteristics [10].

Table 3. Table 3. Relationship between prototype, insert cutting edge, and cutting parameters used in the experiment.

Ball (sample)	Insert – cutting edge	Cutting speed (v_c) (m/min)	Feed (f) (mm/rev)	Depth of cut (ap) (mm)
1	A-1	200	0.08	0.5
2	A-2	240	0.08	0.5
3	A-3	200	0.14	0.5
4	B-1	240	0.14	0.5
5	B-2	200	0.11	0.3
6	B-3	240	0.11	0.3
7	C-1	200	0.11	0.7
8	C-2	240	0.11	0.7
9	C-3	220	0.08	0.3
10	D-1	220	0.14	0.3
11	D-2	220	0.08	0.7
12	D-3	220	0.14	0.7
13*	E-1	220	0.11	0.5
14*	E-2	220	0.11	0.5
15*	E-3	220	0.11	0.5

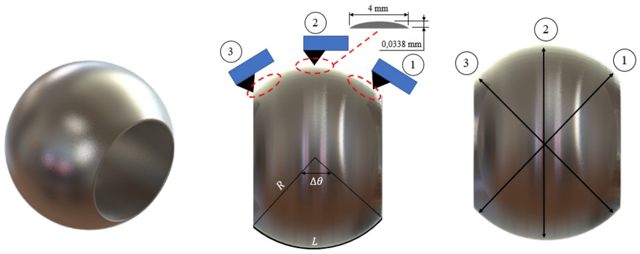
* Cutting parameters currently used in the machining of the balls.

Following the machining of the 15 balls (a representative sample is shown in Figure 4a), visual and dimensional inspections were conducted alongside surface roughness evaluations. The primary objective of these measurements was to identify the machining parameters that resulted in the lowest surface roughness levels.

To evaluate the surface finish, roughness measurements were performed using a Mitutoyo® SJ-210 contact profilometer in accordance with the ISO 4288 standard. As illustrated in Figure 4b, data was collected at three distinct regions on each ball: (1) the right edge, (2) the central region, and (3) the left edge. A Gaussian filter was applied to separate the roughness profile from surface waviness. The sampling length (cut-off, λ_c) configured for these measurements was 0.8 mm, resulting in a total evaluation length (L_n) of 4.0 mm.

A critical consideration during this procedure was the curvature of the ball surfaces (circular arc). When measuring the roughness over the 4.0 mm evaluation length, it was observed that the vertical difference between the start and end of the measurement stroke, relative to the central region, was 0.0338 mm, as shown in Figure 4b. This confirmed the capability of the Mitutoyo® SJ-210 contact profilometer to handle curved geometries. The instrument accommodates a maximum vertical displacement of 0.36 mm with a high resolution of 0.002 µm, allowing the accurate detection of minute roughness variations even on semi-flat or curved profiles [14].

Additionally, the external diameters of the balls (D) were measured at three regions of each piece, as illustrated in Figure 4c: (1) at the center and at both ends near the through bore, points (1) and (3). These measurements were performed using a Mitutoyo® outside micrometer (110 – 200 mm range) with a resolution of 0.01 mm.



(a) (b) (c)

Figure 4. (a) Ball in isometric view; (b) locations of surface roughness measurements; (c) diameter measurement locations.

Calculating the cutting time and material removal rate is essential for process planning, productivity optimization, and estimation of operational costs. In the case of curved surfaces, such as circular arcs, determining the arc length requires specific geometric considerations due to the variation in the tool path. The arc length (L), cutting time (T_c), and material removal rate (MRR) were calculated using Equations (1), (2), and (3), respectively [15].

$$L = R \cdot \Delta\theta \quad (1)$$

$$T_c = \frac{2 \cdot \pi \cdot R \cdot L}{1000 \cdot f \cdot vc} \quad (2)$$

$$MRR = vc \cdot ap \cdot f \quad (3)$$

Where:
L is the arc length (mm);
R is the radius of the ball curvature (mm);
$\Delta\theta$ is the swept angle of the arc (radians);
T_c is the cutting time (min, which was later converted to seconds for comparison);
v_c is the cutting speed (m/min);
f is the feed rate (mm/rev);
ap is the depth of cut (mm);
MRR is the material removal rate (cm³/min).

With the optimal machining parameters determined, six additional balls were manufactured under these conditions using new inserts (F and G), aiming to validate the results indicated by the BBD experimental design.

Results and Discussion

Table 4 presents the mean values and standard deviations (σ) of the roughness parameters (R_a and R_z), as well as the mean values of the external diameter (D_e), material removal rate (MMR), and cutting time (T_c). The machining parameters currently used in the production of the balls were applied to prototypes numbered 13, 14, and 15* (insert E) (v_c = 220 m/min; f = 0.11 mm/rev; ap = 0.5 mm). These parameters resulted in average surface roughness values of R_a = 0.763 µm and R_z = 3.812 µm, as well as material removal rate MMR = 12.1 cm³/min and machining time T_c = 95.22 s. Although these results are intermediate compared to the other tested parameters presented in Table 4, the parts produced under these conditions generally undergo an additional polishing process before being used in the valves. This additional process is intended to minimize roughness values, since, according to the literature [16], for PTFE lip seals, the surface finish of the metallic component (counterbody) is recommended to have a roughness below R_a < 0.4 µm to ensure a fluid-tightness level classified as no visible leakage (NVL).

Among the 15 tested parameter combinations, the one that resulted in the lowest surface roughness values (R_a = 0.390 µm and R_z = 2.573 µm) was applied to sample 9. The selected

Table 4. Average results found for the 15 machined samples.

Balls (samples)	*Ra* (µm)	*σ* (µm)	*Rz* (µm)	*σ* (µm)	*De* (mm)	*MRR* (cm³/min)	*Tc* (s)
1	0.466	0.152	2.859	0.757	118.54 ± 0.01	8.0	144.02
2	0.505	0.265	2.844	1.288	118.55 ± 0.01	9.6	120.01
3	0.733	0.092	4.090	0.560	118.54 ±0.01	14.0	82.29
4	1.075	0.363	5.014	1.078	118.56 ± 0.01	16.8	68.58
5	0.617	0.066	3.255	0.195	118.55 ± 0.01	6.6	104.74
6	0.711	0.069	3.621	0.280	118.55 ± 0.01	7.9	87.28
7	0.761	0.093	3.876	0.542	118.55 ± 0.01	15.4	104.74
8	0.812	0.185	3.974	0.603	118.54 ± 0.01	18.5	87.28
9	0.390	0.083	2.573	0.325	118.54 ± 0.01	5.3	130.92
10	1.280	0.408	5.768	1.446	118.54 ± 0.01	9.2	74.81
11	0.415	0.070	2.826	0.617	118.56 ± 0.01	12.3	130.92
12	1.088	0.491	5.328	1.654	118.56 ± 0.01	21.6	74.81
13*	0.878	0.240	4.331	0.838	118.54 ± 0.01	12.1	95.22
14*	0.660	0.207	3.430	0.643	118.54 ± 0.01	12.1	95.22
15*	0.750	0.217	3.676	0.811	118.54 ± 0.01	12.1	95.22

parameters were: (v_c = 220 m/min; f = 0.08 mm/rev; ap = 0.3 mm). This combination adopted an intermediate cutting speed and the lowest feed rate and depth of cut. Although it provided the best surface finish (the main objective of the present study), the material removal rate (MMR = 5.3 m^3/min) was the lowest recorded. Consequently, the finishing machine time (T_c = 130.92 s) was among the highest.

The parameter set that resulted in the highest surface roughness values (R_a = 1.280 µm and R_z = 5.768 µm) was applied to sample 10. The parameters used were: (v_c = 220 m/min; f = 0.14 mm/rev; ap = 0.3 mm). It can be observed that a maximum feed rate tends to significantly compromise the surface finish. However, this configuration provided a considerable increase in the material removal rate (MMR = 9.2 m^3/min) and, consequently, a reduction in cutting time (T_c = 74.81 s) compared to the parameters used for sample 9.

Figure 5 presents the roughness profiles, obtained from the average of three measurements taken on each ball, as well as the percentage distribution of the measured values. Figures 5a and 5b show, respectively, the average roughness profile and the percentage distribution of the values for ball 13, machined with the parameters currently used in production. Ball 9, which exhibited the lowest roughness levels, is represented in Figures 5c and 5d, while ball 10, shown in Figures 5e and 5f, recorded the highest roughness values. These results highlight that improper selection of cutting parameters can significantly compromise the surface finish of the workpiece.

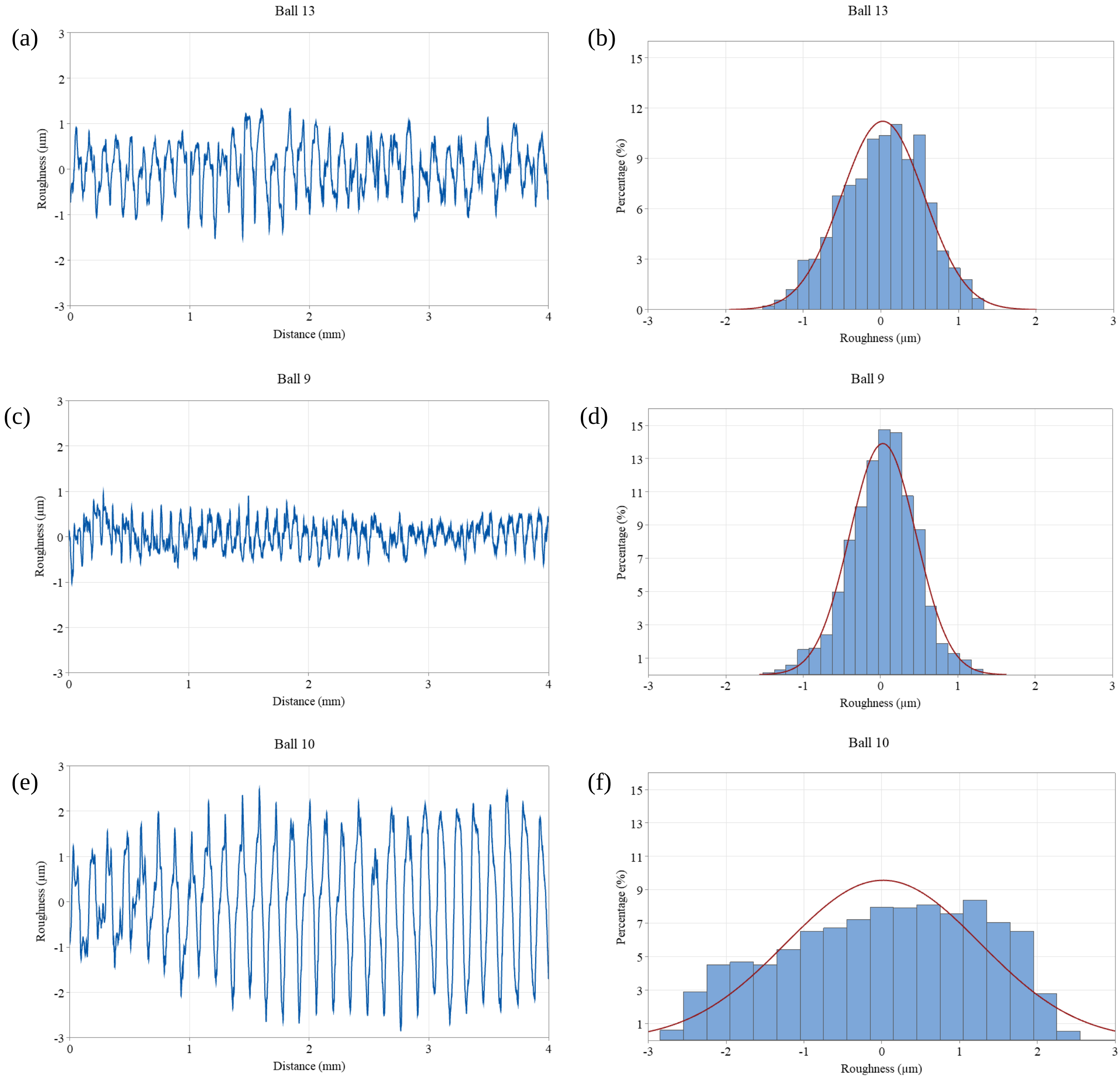


Figure 5. Roughness profile and percentage distribution for the samples: (a) (b) ball 13; (c) (d) ball 9; (e) (f) ball 10.

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The analysis of variance (ANOVA) of the average roughness results (Table 4) highlighted the individual contribution of each cutting parameter to the response: 77.38% attributed to the feed rate (f), 3.72% to the cutting speed (v_c), and only 0.08% to the depth of cut (ap). To assess the significance level of the factors, a 95% confidence interval was adopted, with the criterion (p-value < 0.05). It was found that only the feed rate had a statistically significant effect (p-value = 0.003). Cutting speed (p-value = 0.280) and depth of cut (p-value = 0.865) were not considered significant. The coefficient of determination (R^2 = 87.31%) indicated a good explanatory capability of the model. Second-order (quadratic) terms and factor interactions also did not show statistical significance (p-value > 0.05). Although the experimental design considered a second-order regression model, the results demonstrated that only the linear term of the feed rate (f) was relevant. Therefore, it can be concluded that surface roughness strongly depends on the feed rate, whereas cutting speed and depth of cut, as well as quadratic and interaction effects, do not have a significant influence on the response.

From a fundamental machining perspective, this dominant effect of the feed rate on surface roughness can be explained by the kinematics of the turning process. Theoretically, the peak-to-valley height of a machined profile is primarily governed by the feed rate (f) and the tool nose radius (r_e), often approximated by the geometric relationship $R_z = f^2/(8 \times r_e)$. As the feed rate increases, the distance between successive tool paths widens, leaving more pronounced kinematic marks (feed marks) on the machined surface, which physically manifests as higher R_a and R_z values. This kinematic behavior makes the feed rate the most critical control variable for surface finish.

The feed rate is the most significant parameter in achieving better surface roughness in the machining of austenitic stainless steel AISI 316 has also been reported in several studies, some of which are presented below.

Shareef et al. [17] conducted a study using the Central Composite Design (CCD) method, based on the Response Surface Methodology (RSM), in turning tests with PVD-TiAlN inserts, aiming to investigate the machinability of stainless steels AISI 303, 304, 316, 416, and structural steel A36. Machinability was evaluated based on surface roughness, energy consumption, chip morphology, and dimensional accuracy. The results indicated that AISI 316 exhibited the best surface finish, with the feed rate being the most influential factor in this behavior.

Rajaparthiban et al. [18] investigated the turning of AISI 316 stainless steel with the aim of determining the optimal cutting conditions to minimize surface roughness and maximize the material removal rate. The study employed the Taguchi method for experimental design, and the ANOVA revealed that the feed rate was the most significant parameter, contributing 61.51% to the analyzed response.

Basmaci [19] analyzed the turning of AISI 316L stainless steel with the objective of optimizing machining parameters to achieve the best surface finish. The study considered feed rate, depth of cut, and different lubrication-cooling conditions as input factors: dry, minimum quantity lubrication (MQL), and flood coolant. The Taguchi method and ANOVA were applied, and the results indicated that the feed rate was the most influential parameter on surface finish, with increases in feed rate proportionally raising roughness values.

Bagaber and Yusoff [20] conducted a study aimed at optimizing the dry turning process of AISI 316 stainless steel using uncoated carbide tools. The authors applied Response Surface Methodology (RSM) combined with multi-objective optimization to determine the cutting parameters (cutting speed, feed rate, and depth of cut) that simultaneously minimize energy consumption, surface roughness, and tool wear. Statistical analysis demonstrated that the feed rate was the most significant factor in determining surface roughness.

Continuing the analysis of the results of the present study, contour plots were generated considering the feed rate fixed at its minimum level (f = 0.08 mm/rev) while varying the cutting speed (v_c) and depth of cut (ap). These plots allowed the observation of the possible values of average roughness (R_a) and maximum roughness (R_z) that could be achieved. As illustrated in Figure 6a (R_a) and Figure 6b (R_z), it is possible to visualize the surface roughness values obtained for different

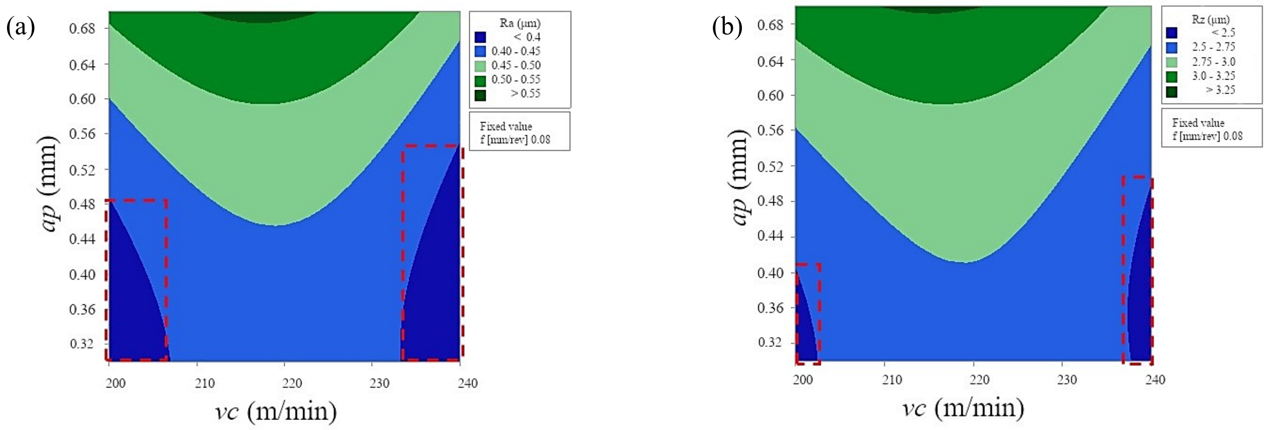

Figure 6. Contour plots (RSM) for f = 0.08 mm/rev. (a) R_a; (b) R_z.

combinations of cutting speed (v_c) and depth of cut (ap). The operational regions that resulted in the best surface finishes are highlighted with red dashed lines, indicating the most favorable machining conditions: (v_c = 200 m/min, f = 0.08 mm/rev, ap = 0.3 mm) and (v_c = 240 m/min, f = 0.08 mm/rev, ap = 0.5 mm). These parameters allow the achievement of roughness profiles (R_a < 0.4 µm and R_z < 2.5 µm), which correspond to the targets established in this study.

Subsequently, the analysis of the results obtained from the machining of the 15 samples (Table 4) was complemented by applying the response optimization tool using Minitab® 22 software, aiming to achieve minimum roughness values (R_a and R_z). The optimized solution indicated the following parameters: (v_c = 200 m/min, f = 0.08 mm/rev, and ap = 0.3 mm), corresponding to the minimum levels (-1) defined in Table 2. Under these conditions, the model predicted R_a = 0.361 µm and R_z = 2.435 µm, showing that the average roughness meets the requirement of R_a < 0.4 µm, necessary to ensure the proper performance of valves with PTFE sealing elements.

In line with these results, the previously presented contour plots (RSM) (Figures 6a and 6b) confirm the adequacy of the minimum machining parameters, but also indicate the possibility of using higher cutting speed and depth of cut values: (v_c = 240 m/min, f = 0.08 mm/rev, and ap = 0.5 mm), which can reduce machining time and increase the material removal rate. This alternative offers the advantage of shorter cutting time and increased productivity without compromising the specified surface quality.

Considering the optimized parameters, six new balls were machined, three for each cutting configuration. Balls numbered 16, 17, and 18 make up the group referred to as Optimization I, while balls 19, 20, and 21 belong to the group Optimization II. For these machining tests, two new cutting inserts, identified as G and H, were used, adopting the criterion of employing a new cutting edge for each ball. Thus, the same procedure was applied during the machining of the 15 prototype balls in the initial phase of the study. The corresponding information is presented in Table 5.

Table 5. Relationship between group, prototype, insert edge, and optimized cutting parameters used in the experiment.

Group	Balls (samples)	Insert – edges used	v_c (m/min)	f (mm/rev)	ap (mm)
Optimization I	16	F-1	200	0.08	0.3
Optimization I	17	F-2	200	0.08	0.3
Optimization I	18	F-3	200	0.08	0.3
Optimization II	19	G-1	240	0.08	0.5
Optimization II	20	G-2	240	0.08	0.5
Optimization II	21	G-3	240	0.08	0.5

Table 6 shows the results obtained for the optimized samples. It can be observed that, in both groups, it was possible to achieve average surface roughness (R_a < 0.4 µm and R_z < 2.5 µm), confirming the results predicted by the methodology for the parameters used in Optimization I and II groups. Therefore, in terms of surface finish, there is a technical tie between the two sets of parameters. Dimensional accuracy of the external diameter of the balls was also maintained in both cases.

Table 6. Average results obtained for prototypes 16 to 21.

Balls (samples)	R_a (µm)	σ (µm)	R_z (µm)	σ (µm)	External diameter (mm)	MRR (cm³/min)	T_c (s)
16	0.387	0.015	2.207	0.159	118.55 ± 0.01	4.8	144.02
17	0.389	0.009	2.311	0.070	118.54 ± 0.01	4.8	144.02
18	0.377	0.007	2.121	0.006	118.54 ± 0.01	4.8	144.02
19	0.381	0.017	2.257	0.103	118.55 ± 0.01	9.6	120.01
20	0.337	0.026	1.982	0.231	118.53 ± 0.01	9.6	120.01
21	0.348	0.013	1.904	0.170	118.53 ± 0.01	9.6	120.01

The advantage lies with Optimization II, both in terms of machining time (120.01 s) and material removal rate (9.6 cm³/min), compared to Optimization I (144.02 s and 4.8 cm³/min, respectively), representing a 16.67% reduction in machining time and a 100% increase in material removal rate. Figures 7a and 7b present the average roughness profile and percentage variation for ball 18, chosen as the representative of the Optimization I group, while Figures 7c and 7d correspond to ball 19, selected as the representative of the Optimization II group, confirming the technical tie between the two parameter groups.

Figure 8 presents comparative graphs of the main results obtained for the balls analyzed. Ball 10 corresponds to the worst roughness found, ball 13 represents the currently used manufacturing parameters, ball 9 showed the best roughness levels among the 15 initially machined samples, while balls 18 and 19 correspond to the conditions of Optimization I and Optimization II, respectively. The results show consistent trends between machining time, material removal rate, and surface roughness. Ball 10 exhibited the shortest machining time (74.81 s) and a high material removal rate (9.24 cm³/min), but with the poorest surface finish (R_a = 0.878 µm; R_z = 5.768 µm). Ball 13, representing the current manufacturing process, achieved an intermediate surface finish (R_a = 0.878 µm; R_z = 4.331 µm), a machining time of 95.22 s, and the highest material removal rate (12.1 cm³/min). However, the current manufacturing process requires an additional polishing step after turning to reduce the ball roughness before valve assembly.

Ball 9 exhibited the lowest roughness values among the initial samples (R_a = 0.390 µm; R_z = 2.573 µm), but with a high machining time (130.92 s) and a low material removal rate (5.28 cm³/min). Ball 18 (Optimization I), on the other hand, achieved low surface roughness (R_a = 0.377 µm;

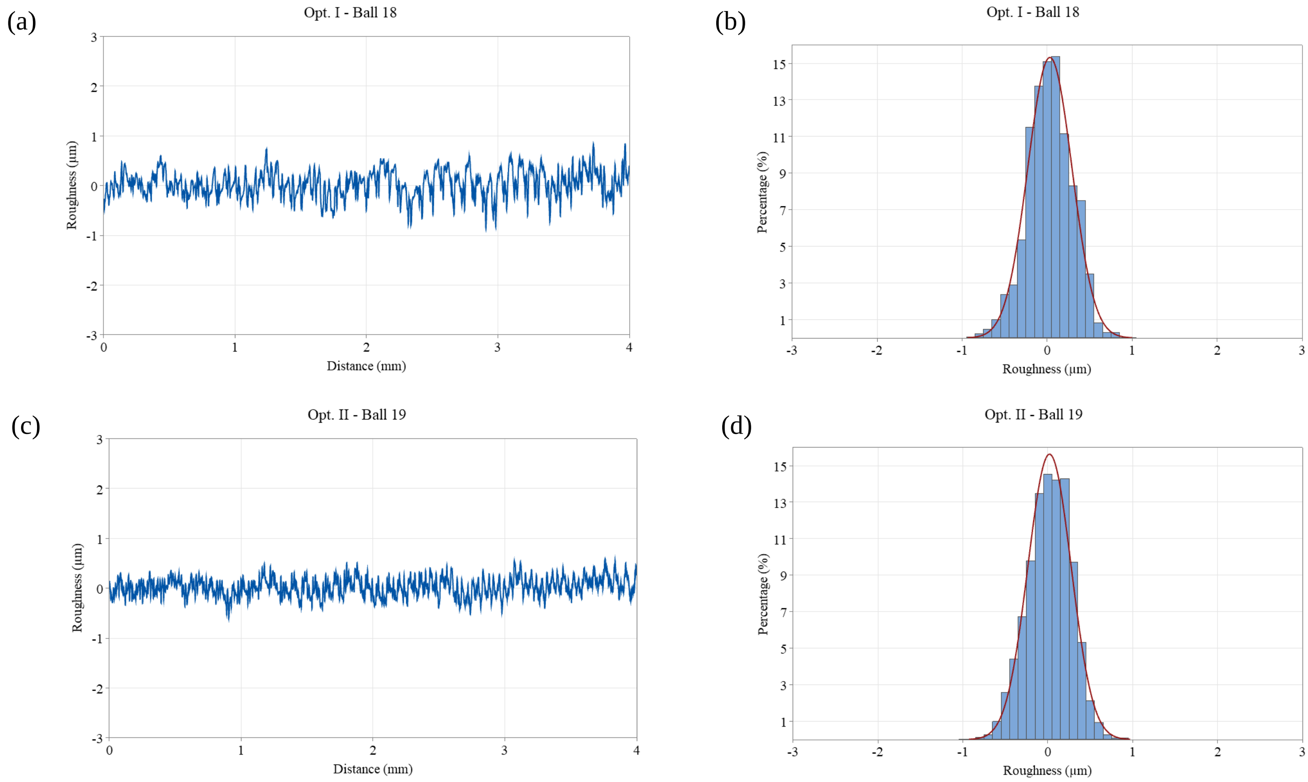

Figure 7. Roughness profile and percentage distribution for the samples: (a) and (b) Opt. I – ball 18; (c) and (d) Opt. II – ball 19.

R_z = 2.121 µm), but had the longest machining time (144.02 s) and the lowest material removal rate (4.8 cm³/min). Ball 19 (Optimization II) also presented low roughness values (R_a = 0.381 µm; R_z = 2.257 µm), with a significant improvement in machining time (120.01 s) and material removal rate (9.6 cm³/min). The balls that met the acceptance criterion (R_a < 0.4 µm) were ball 9, as well as those in the Optimization I and Optimization II groups. The optimized samples also exhibited the lowest maximum roughness values (R_z).

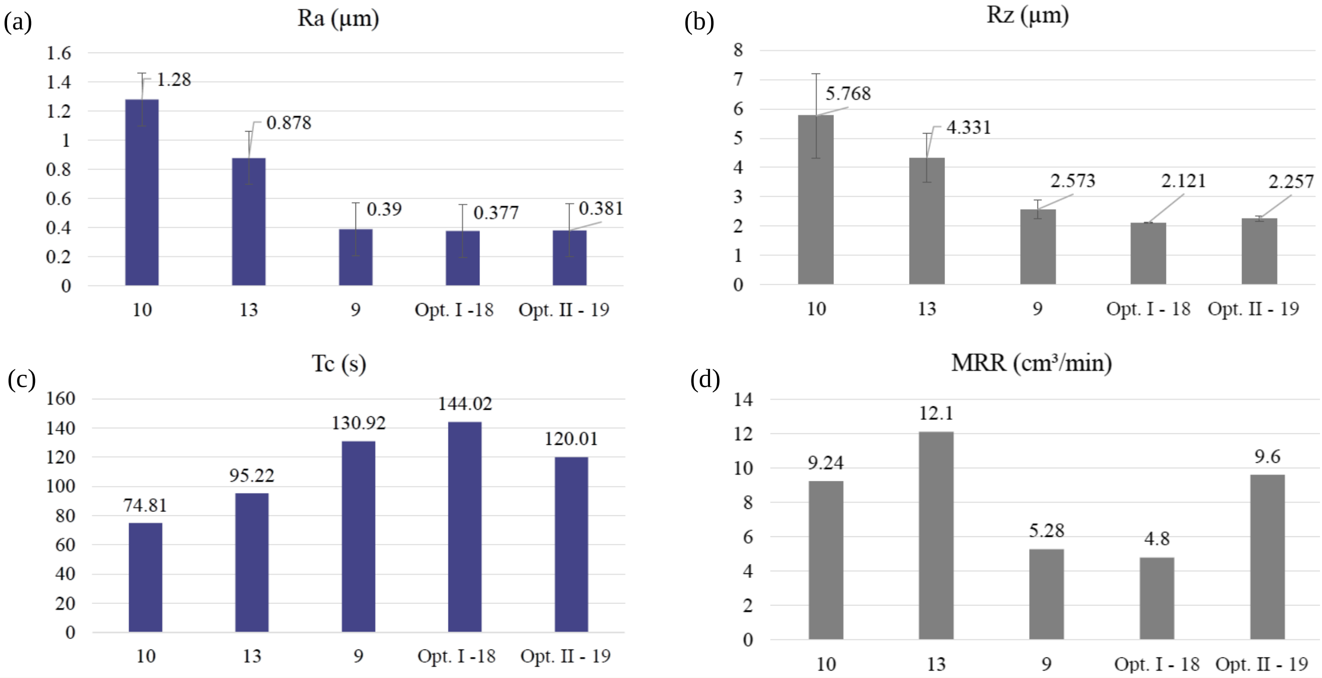

Figure 8. Comparative graphs: (a) R_a; (b) R_z; (c) cutting time T_c and (d) Material removal rate *MRR* .

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Among the experimental parameters, those applied in Optimization II were considered the most suitable because, in addition to ensuring roughness within the acceptable limit ($R_a < 0.4$ µm), they reduced machining time by approximately 8.3% and increased the material removal rate by about 81.8% compared to the conditions of ball 9. In relation to Optimization I (ball 18), the Optimization II parameters provided an additional 16.7% reduction in machining time and a 100% increase in material removal rate while maintaining similar surface roughness levels.

Therefore, the parameters defined in Optimization II are the most recommended for improving the production process of the valve ball component under study. This comparative analysis clearly highlights the inherent trade-off between surface finish quality and manufacturing productivity. While lower feed rates are essential to suppress kinematic feed marks and achieve the tight roughness tolerances required for PTFE sealing elements, they inherently penalize the material removal rate and prolong cutting times. However, Optimization II demonstrates that a strategic selection of depth of cut and cutting speed can counterbalance this productivity loss without sacrificing the surface finish. In an industrial context, particularly in the scaling and manufacturing of critical components like industrial ball valves for rigorous fluid applications, finding this optimal balance has significant practical implications. By adopting the Optimization II parameters, manufacturers can successfully eliminate the subsequent manual or semi-automated polishing operations. This not only streamlines the production route and reduces direct manufacturing costs but also enhances the overall repeatability of the manufacturing process, allowing for higher throughput of valve components that consistently meet stringent no visible leakage (NVL) standards.

Conclusions

The present study demonstrated that the application of a Box-Behnken Design (BBD) combined with the Response Surface Methodology (RSM) constitutes an effective tool for optimizing cutting parameters in the turning of cast austenitic stainless-steel ASTM A351 CF8M, a material widely used in the manufacture of industrial valve balls. Analysis of variance showed that the feed rate (f) is the most influential factor on surface roughness, accounting for 77.38% of the observed variability, while cutting speed (v_c) and depth of cut (ap) had secondary effects of low significance. The optimized cutting conditions (v_c = 200–240 m/min, f = 0.08 mm/rev, and ap = 0.3 –0.5 mm) enabled the achievement of average roughness values ($R_a < 0.4$ µm), meeting surface finish requirements to ensure leak-free sealing in valves with PTFE sealing elements.

Experimental validation confirmed the accuracy of the predictive model, showing an approximate 48% reduction in average roughness compared to the currently employed process ($R_a \approx 0.8$ µm) without compromising the specified dimensional tolerances. In addition to improving surface finish quality, the study demonstrated that it is possible to achieve more efficient machining conditions, combining lower roughness, increased productivity, and dimensional stability. From a practical standpoint, the capability to achieve the required $R_a < 0.4$ µm strictly through the turning process allows for the complete elimination of subsequent polishing operations. This provides a direct industrial benefit by significantly reducing overall manufacturing lead times and operational costs. Thus, the proposed BBD-RSM methodology has direct applicability in the valve industry, serving as a technical reference for selecting cutting parameters for low-machinability materials, such as cast austenitic stainless steels.

Finally, it is noteworthy that the employed systematic approach can be extended to other sizes and geometries of balls, as well as to different material classes, contributing to the advancement of more precise, economical, and sustainable manufacturing practices in the metalworking sector.

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Authors Contribution

L. C. B. Bertocco: Investigation, Data Curation, Formal Analysis, Writing – original draft; D. B. Teles: Conceptualization, Methodology, Investigation, Formal analysis, Supervision, Writing - review & editing; A. J. de Souza: Validation, Writing - review & editing. All authors have approved the final version of the manuscript.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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