SURFACE TOPOGRAPHY IMPROVEMENT OF 18CRNIMO7-6 STEEL USING THE TAGUCHI TECHNIQUE

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Abstract

The ball burnishing process provides a fast, cost-effective, and straightforward method to enhance the physical-mechanical properties and surface integrity of industrially manufactured parts. In this study, ball burnishing was applied to improve the surface topography of 18CrNiMo7-6 steel, with milling used as a pre-burnishing treatment. A Taguchi L9 orthogonal array was employed to conduct hydrostatic ball burnishing investigations and optimal values of the process parameters have been identified. The positive effect of the burnishing process on a number of surface topography parameters was also demonstrated.

Keywords: ball burnishing, surface topography, roughness, Taguchi technique.

I. Introduction

Surface topography plays a crucial role in mechanical engineering. It considerably affects the friction and wear properties of interacting materials, thereby influencing their tribological behavior [1]. Additionally, surface topography governs surface properties such as adhesion and stiffness, which are very important for material performance [2]. Moreover, variations in surface structure can lead to differences in other mechanical properties, such as fatigue strength and lubrication efficiency [3].

The condition of surface topography can be influenced by most elements of the manufacturing process; however, the finishing treatment has a decisive influence. Depending on the main purpose of the finishing treatment, it can be smoothing or strengthening [4]. One of the types of finishing treatment is the burnishing process (plastic deformation treatment of the surface) used, among other purposes, to achieve low values of surface roughness parameters. The authors of the work [5] applied the ball burnishing process to improve the final quality of form tools (moulds and dies). They reported that by using the optimal input parameters it is possible to reduce the arithmetical mean roughness Ra from 3.01 μm to approximately 0.30 μm, while an initial hardness (HRA) of about 66.35 can be increased to 71.33. The purpose of the research by Rodriguez et al. [6] was to improve of surface topography properties of 2050 aluminum components with two different heat treatments. The authors concluded that ball burnishing enhanced surface finish, hardness, and fatigue life of components. They also identified optimal parameters for burnishing aluminum alloy components. The positive effect of ball burnishing process on reducing surface roughness parameters and increasing hardness was also noted by the authors of [7, 8]. Dzionk et al. [9] analyzed the changes in surface topography of the shafts after ceramic ball burnishing. They revealed that the application of ball burnishing allowed for the achievement of surfaces suitable for high-performance applications, such as rolling bearings and hub joints. Livatyali [10] indicated that ball burnishing improves surface integrity of thin Ti6Al4V flat sheets by inducing compressive residual stresses. The advantages of compressive residual stresses in the surface layer of components were also highlighted by the authors of [11].

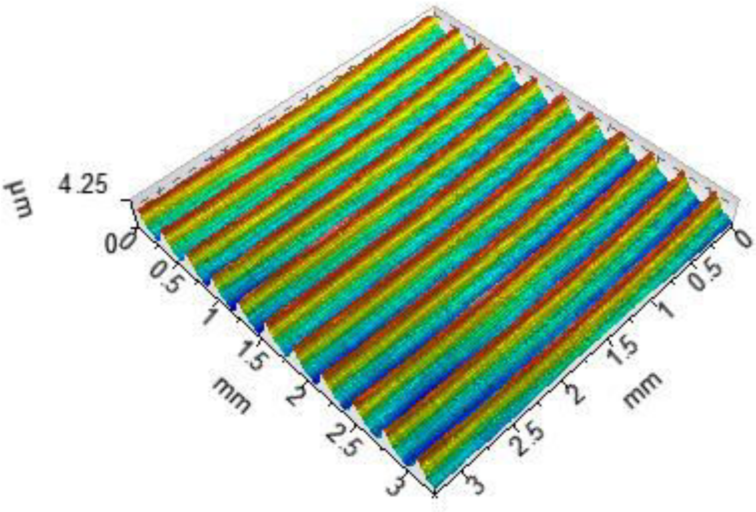
Currently, the surface burnishing process dominates in the machining of rotational surfaces - such as on lathes, boring machines - sometimes effectively replacing grinding or honing. Dynamic burnishing is often used for non-rotary surfaces [12, 13], providing good strengthening effects, but significantly poorer dimensional and smoothness effects. Therefore, the aim of this study was to analyze the effect of hydrostatic ball burnishing parameters on selected geometric structure parameters of flat surfaces after the milling process.

II. Experimental procedure

In the present article, 18CrNiMo7-6 steel with a hardness of 45±2 HRC was chosen to investigate the influence of hydrostatic ball burnishing on surface topography parameters. The burnishing tool with a 10 mm ceramic Al2O3 ball was installed in Haas CNC Vertical Mill Center VF-3. The test samples were shaft sections with a diameter of 25 mm and a height of 8 mm. The medium used for the process was a water-and-oil emulsion, Hysol. Hydrostatic ball burnishing was carried out using the following parameters:

- Burnishing pressure: 10; 20 and 30 [MPa],
- Burnishing velocity: 750; 1500 and 2250 [mm/min],
- Burnishing width: 0.04; 0.08 and 1.2 [mm].

Milling was performed as a pre-burnishing treatment. All samples were milled to achieve an arithmetical mean height of the surface (Sa) of 0.72 μm. The isometric view of the milled surface, along with various surface topography parameters, is presented in Figure 1. A detailed description of these surface topography parameters – skewness (Ssk), kurtosis (Sku), maximum height of the surface (Sz), texture aspect ratio (Str), peak density (Spd), developed area ratio (Sdr), core roughness depth (Sk), reduced peak height (Spk) and reduced valley depth (Svk) – is available in [14, 15]. Surfaces after the milling process were characterized by positive values of skewness which may indicate a more bumpy nature of the surface. We can reach similar conclusions considering the ratio of Spk to Svk – value of reduced peak height is higher then reduced valley depth. Texture aspect ratio (Str) is at the level of 0.0369, which indicates a clear anisotropy of the surface.



Sa	0.72 [μm]
Ssk	0.544
Sku	2.20
Sz	4.28 [μm]
Str	0.0369
Sdr	0.105 [%]
Spd	103 [1/mm²]
Sk	1.72 [μm]
Spk	1.21 [μm]
Svk	0.0999 [μm]

Figure 1: *Isometric view of the base surface and selected surface topography parameters*

Before and after hydrostatic ball burnishing process, the surface topography of all samples was measured using a white light interferometer Talysurf CCI Lite. A 5*x* lens was used in the measurements to obtain a measurement area of 3.3 mm x 3.3 mm. After measurement surfaces were leveled using the TalyMap 6.0 software – digital filtration was not used.

Taguchi L9 orthogonal array was used to perform investigations (Table 1). In G. Taguchi's plans, during the implementation and mathematical analysis of research results, the signal, noise and control

Table 1: *Design of experiment*

Exp. number	Input burnishing parameters and their levels		
	Pressure [MPa]	Velocity [mm/min]	Width [mm]
1	10	750	0.04
2	10	1500	0.08
3	10	2250	1.2
4	20	750	0.08
5	20	1500	1.2
6	20	2250	0.04
7	30	750	1.2
8	30	1500	0.04
9	30	2250	0.08

factors are considered. Noise (process disturbances) takes into account the influence of factors that are beyond the operator's control, while the operator sets the control factors during machining. In ideal conditions, the output signal (surface roughness after burnishing) will only react to the operator's signals and will not react to random changes during machining. In Taguchi technique [16, 17, 18], a loss function is used to calculate the deviation between the experimental value and the desired value. This loss function is then converted into a signal-to-noise (S/N) ratio. Various types of S/N ratios are available, depending on the nature of the characteristics involved:

- lower is better,
- nominal is better,
- higher is better.

In the case of "higher is better" and "lower is better" ratio, the definitions of the loss function for hydrostatic ball burnishing process are as follows:

$$Lower\ is\ better = -10log\left[\frac{1}{n}\right]\sum_{i=1}^{n} y_i^2 \quad (1)$$

$$Higher\ is\ better = -10log\left[\frac{1}{n}\right]\sum_{i=1}^{n} y_i^{-2} \quad (2)$$

where n is the number of measurements and y_i is the measured value. In our study "lower is better" ratio was applied.

III. Results and discussion

Table 2 presents selected surface topography parameters achieved after hydrostatic ball burnishing. The arithmetical mean height of the surface (Sa) decreased significantly as a result of the

Table 2: *Results of the experiments*

Exp. number	Sa [μm]	Sz [μm]	Sdr [%]	Ssk	Sk [μm]	Spk [μm]	Svk [μm]
1	0.253	1.45	0.0239	-0.502	0.732	0.0264	0.31
2	0.378	2.39	0.0373	-0.165	1.23	0.0875	0.262
3	0.43	3.27	0.0511	0.00843	1.66	0.206	0.253
4	0.291	1.79	0.0268	-0.297	0.954	0.111	0.296
5	0.307	2	0.0301	-0.201	0.902	0.182	0.274
6	0.166	1.79	0.0159	-1.07	0.372	0.0947	0.36
7	0.261	1.75	0.0219	-0.123	0.785	0.178	0.287
8	0.051	0.596	0.00402	-0.117	0.145	0.0421	0.0522
9	0.181	1.38	0.0141	-0.123	0.589	0.111	0.164

process with values ranging from 0.051 μm (sample 8) to 0.43 μm (sample 3). A similar trend was observed for the maximum height of the surface (Sz), which, compared to the milling process (Sz = 4.28 μm), was reduced to between 0.056 and 3.27 μm. Skewness (Ssk), which measures the symmetry of surface variation about its mean plane, also decreased and showed negative values in almost all samples, indicating a predominance of valleys. The only exception was sample 3, where Ssk was 0.008. Surfaces after burnishing, like those after milling, were characterized by high anisotropy, with an Str parameter below 0.1. Analysis of changes in the Sk family group showed a visible reduction in the Spk parameter value, while changes in the Svk parameter were significantly smaller. This suggests that modifications to the surface texture occurred primarily in the peak and core areas, with less change in the valley regions. The developed interfacial area ratio Sdr decreased distinctly compared to the milling process reaching values close to zero. Isometric views of selected surface topography after ball burnishing process are presented in Figure 5.

To assess the effect of burnishing process input parameters on surface topography, the signal-to-noise ratio and means were calculated (Tables 3-5). These factors are presented graphically in Figures 2-4. The parameters Sa, Sz and Sdr were selected for detailed analysis. Response tables for S/N ratio and means of Sa, Sz and Sdr indicate the optimal levels of input parameters for minimizing surface topography values. Analysis of the data shows that burnishing pressure and burnishing width play significant roles in reducing surface roughness across all analyzed parameters. It was confirmed for all analyzed parameters. Although the influence of burnishing velocity was smaller, it should not be considered insignificant. The optimal hydrostatic ball burnishing performance for surface topography

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Table 3: *Response table for S/N ratio and means of Sa*

S/N ratio				Means			
Level	Pressure [MPa]	Velocity [mm/min]	Width [mm]	Level	Pressure [MPa]	Velocity [mm/min]	Width [mm]
1	8.982	11.442	17.795	1	0.3670	0.2683	0.1567
2	12.192	14.852	11.340	2	0.2547	0.2453	0.2833
3	17.454	12.334	9.494	3	0.1643	0.2723	0.3460
Delta	8.472	3.314	8.301	Delta	0.2027	0.0270	0.1893
Rank	1	3	2	Rank	1	3	2

Table 4: *Response table for S/N ratio and means of Sz*

S/N ratio				Means			
Level	Pressure [MPa]	Velocity [mm/min]	Width [mm]	Level	Pressure [MPa]	Velocity [mm/min]	Width [mm]
1	-7.029.	-4.382	-1.263	1	2.370	1.663	1.276
2	-5.378	-3.031	-5.141	2	1.860	1.662	1.853
3	-1.054	-6.049	-7.057	3	1.242	2.147	2.340
Delta	5.974	3.017	5.794	Delta	1.128	0.485	1.061
Rank	1	3	2	Rank	1	3	2

Table 5: *Response table for S/N ratio and means of Sdr*

S/N ratio				Means			
Level	Pressure [MPa]	Velocity [mm/min]	Width [mm]	Level	Pressure [MPa]	Velocity [mm/min]	Width [mm]
1	28.94	32.35	38.77	1	0.037	0.024	0.015
2	32.61	35.64	32.34	2	0.024	0.024	0.026
3	39.37	32.94	29.62	3	0.013	0.027	0.034
Delta	10.43	3.28	8.96	Delta	0.024	0.003	0.020
Rank	1	3	2	Rank	1	3	2

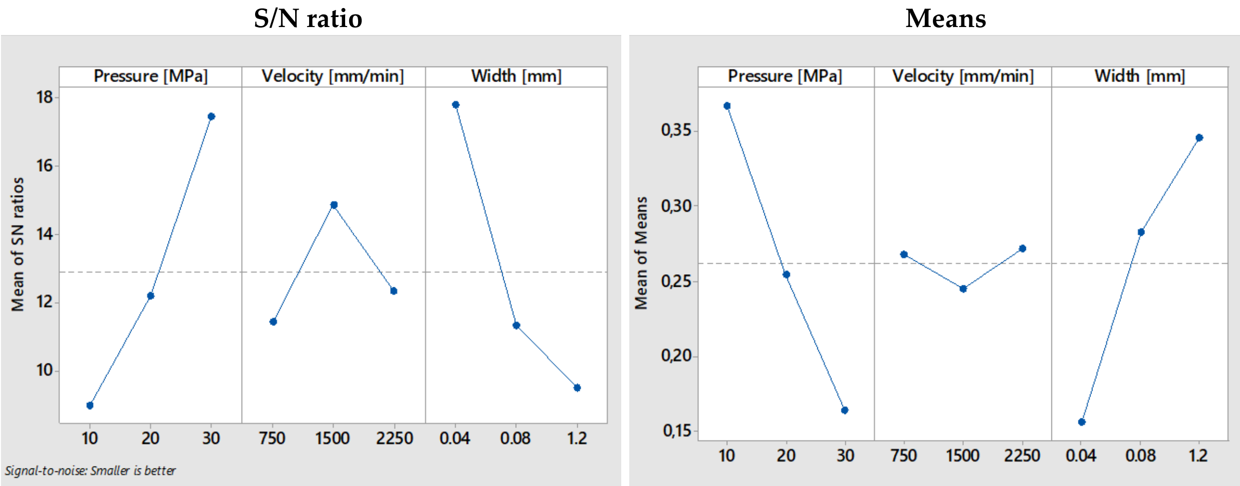


Figure 2: *Main effect plots for the S/N ratio and means of Sa parameter*

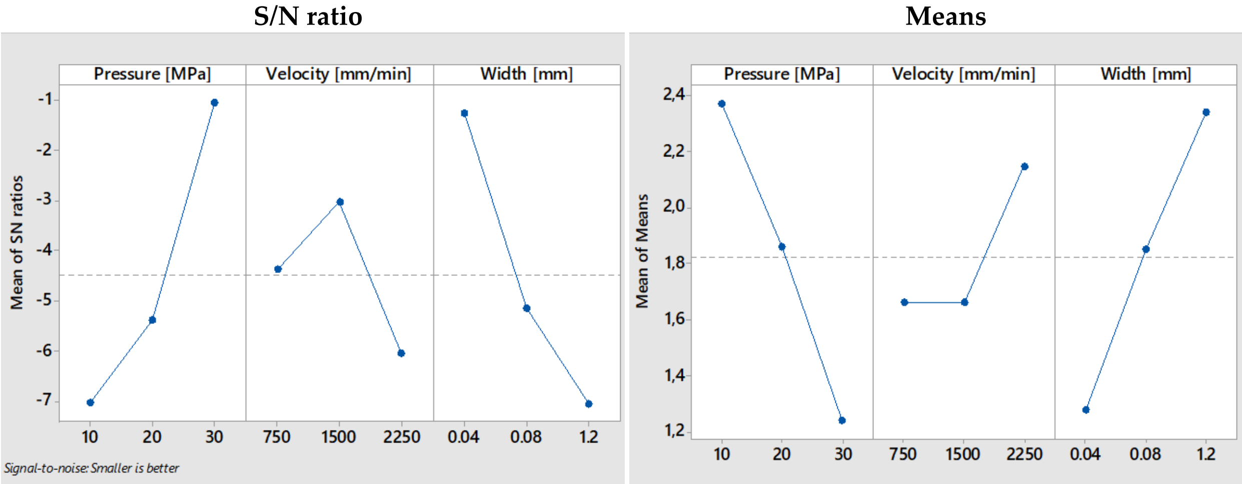


Figure 3: *Main effect plots for the S/N ratio and means of Sz parameter*

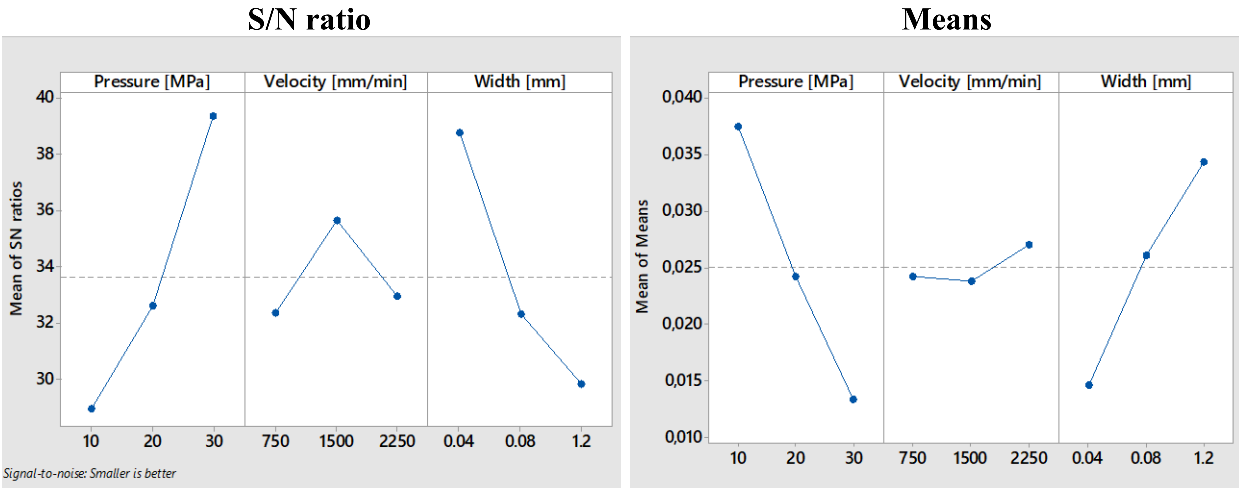
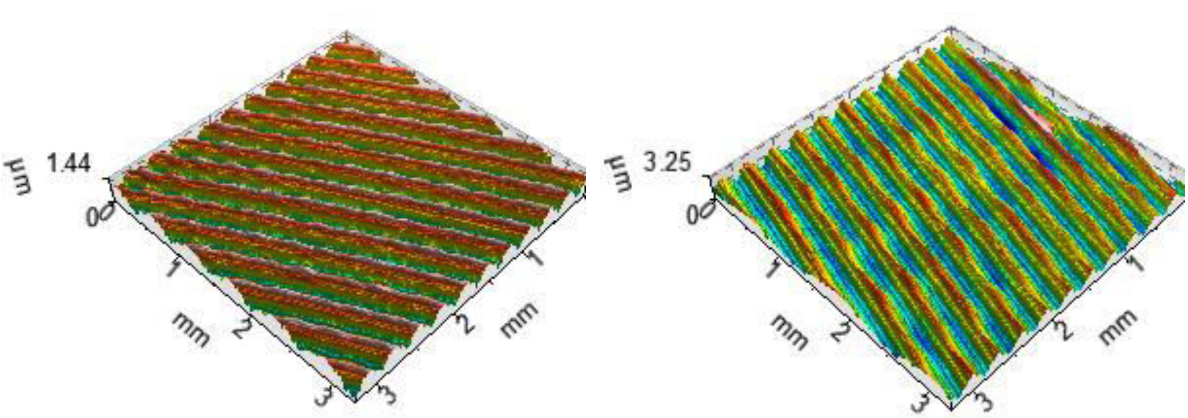


Figure 4: *Main effect plots for the S/N ratio and means of Sdr parameter*

parameters were achieved with the following settings: burnishing pressure – 30 [MPa]; burnishing velocity – 1500 [mm/min] and burnishing width – 0.04 [mm]

Low burnishing pressure causes the burnishing ball to penetrate only shallowly into the metal surface, resulting in plastic flow of the metal. This action reduces surface roughness parameters. In the tests, surface roughness was observed to decrease as burnishing force increased.

a) b)



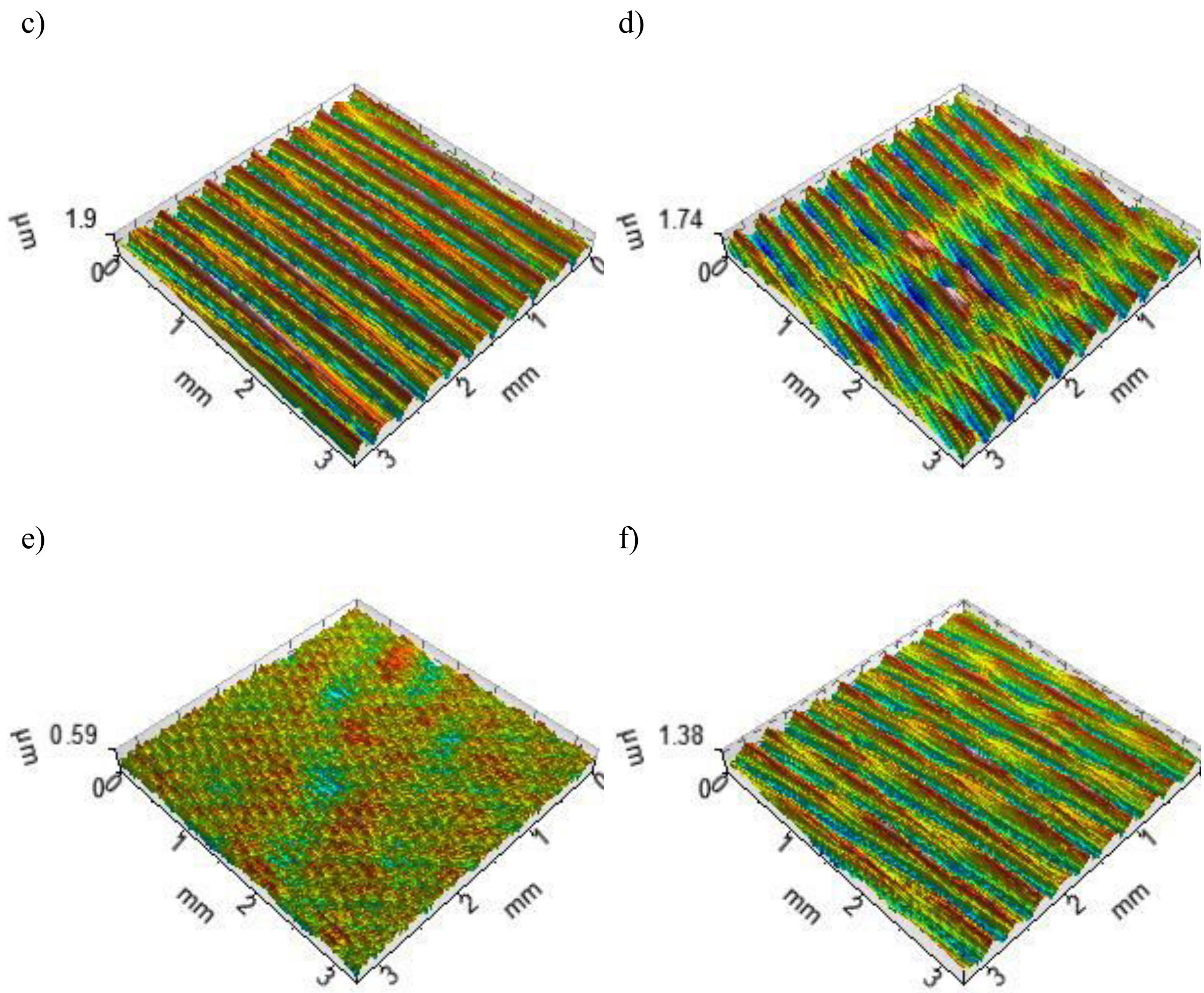


Figure 5: *Isometric views of the selected surface topography after the burnishing process: sample 1 (a), sample 3 (b), sample 4 (c), sample 7 (d), sample 8 (e), sample 9 (f)*

This effect can be attributed to the higher pressure exerted by the ball on the workpiece surface, which compresses most surface irregularities and enhances metal flow. This process fills more of the empty spaces or valleys created in the subsurface layer during processing. It is well known that each material has a specific cold-working capability and a certain work hardening limit. Exceeding this limit would likely lead to an increase in surface roughness. However, based on the tests conducted, it can be concluded that this limit has not yet been reached. Burnishing width was also one of the very important parameters that affect the results of the process. The most favorable width of the machining traces was found to be 0.04 mm. Increasing this width led to higher values in the analyzed roughness parameters. It appears that at the smallest trace width, the distance between machining traces is minimal allowing the tool has sufficient time to smooth the surface effectively. Although the influence of burnishing velocity on the analyzed roughness parameters was smaller than other input parameters, it seems that the most favorable velocity is 1500 mm/min.

IV. Conclusions

This study investigates the hydrostatic ball burnishing process of 18CrNiMo7-6 steel using the Taguchi technique. Based on the analysis of experimental results, the following conclusions can be drawn:

1. The experiments conducted showed that two input factors in the burnishing process – burnishing pressure and burnishing width – significantly influenced changes in surface topography parameters: arithmetical mean height of the surface (Sa), maximum height of the surface (Sz), and developed area ratio (Sdr). In contrast, the effect of burnishing velocity on these parameters was less pronounced.

2. Signal-to-noise ratio analysis revealed that the best surface roughness (minimum values of Sa, Sz and Sdr parameters) was obtained at 30 MPa burnishing pressure, 0.04 mm burnishing width, and 1500 mm/min burnishing velocity.

3. The ball burnishing process applied to the 18CrNiMo7-6 steel produced a new, refined surface layer that improved surface topography. All height parameters were significantly reduced, with the Sa parameter reaching of 0.051 μm in the most favorable variant (sample 6). A positive effect of the burnishing process was also observed in parameters from the Sk family, with the most significant changes occurring in the peak and core parts. All of these beneficial effects were achieved with a single tool pass.

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