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Possibility of Using the Hydrostatic Burnishing Process under Marine Conditions

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ABSTRACT

The publication presents the results of research on the influence of hydrostatic burnishing process on the value of selected parameters of surface roughness, material ratio and surface hardness. The process was carried out on shafts made of the X5CrNi18-10 stainless steel. The prepared samples were subjected to a finishing turning process with constant cutting parameters, and then hydrostatic burnishing was performed on the surface. The tests determined the influence of the variable pressure exerted by the ball on the shaft surface. The evaluation of the research results showed a significant increase in hardness in the surface layer and an improvement in surface roughness parameters and material ratio. The machining process was carried out on a conventional lathe.

Keywords: stainless steel, burnishing treatment, surface roughness, material ratio, relative surface hardening index.

INTRODUCTION

Surface irregularities as well as defects, such as tool marks and roughness, appear on the surface of the workpiece after traditional processes, for instance turning and milling. These irregularities lead to increased friction and surface damage, which shortens the life of the product, lowers its metallurgical properties and generally reduces the quality of the product. To eliminate these defects, conventional surface finishing methods, such as grinding, honing and lapping, are used. These methods are mainly based on the removal of material to obtain the desired finish and their effectiveness is highly dependent on the skill and experience of the operator. To solve these problems, the polishing process is used, which allows for obtaining a better surface finish of the machined parts due to its chipless nature and relatively simple operations [1]. The technology used in the production process significantly influences the durability of machine components. During finishing processing, the final dimensions and functional properties of a given element are assured. This is achieved by using the appropriate type of processing and selecting the correct technological parameters of the process. One of the mechanical processing methods that allows for the creation of a surface layer with particularly beneficial properties is burnishing. This processing uses the phenomenon of surface cold plastic deformations generated in the surface layer of the object. Therefore, the burnishing process changes the geometric structure of the surface. Burnishing technology can be used in machinery industry plants in both unit and series production. It allows elimination of traditional abrasive processing, such as grinding, superfinishing, smoothing or polishing. Therefore, the final shaping of dimensions and functional properties by burnishing is a chip-free and dust-free process. This allows it to be classified as an ecological processing method. The information regarding the burnishing process described above was based on the literature of Przybylski [2, 3]. Professor Przybylski is recognised as a leading expert in the field of burnishing.

Hydrostatic burnishing is a tool used in metal forming processes, which allows for obtaining high surface quality and improving the mechanical properties of the material. It is used in many industries. Owing to this process, the surface becomes more uniform, its roughness is reduced, and minor imperfections are eliminated, which is particularly important in precision industrial components. Hydrostatic burnishing increases the fatigue strength of components by introducing compressive stresses in the surface layer of the material. These stresses counteract the propagation of microcracks, which significantly extends the life of components exposed to cyclic loads.

Hydrostatic burnishing can improve the tribological properties of the surface, such as reducing the coefficient of friction and increasing wear resistance. This is particularly important in the components that operate in high friction conditions, e.g. in bearings, guides or gears. Product quality is becoming increasingly important in the competitive environment of modern production [4]. The industry demands parts with exceptional precision, surface finish, wear resistance, and corrosion resistance. These components are subjected to high mechanical, chemical, and thermal stresses, where the majority of machine element failures stem from inadequate surface parameters or production process errors in surface layers [5]. According to Kalisz et al. [6] obtained significant improvement in surface finish after burnishing compared to polishing. The paper presents an evaluation of the sequential process of milling and burnishing of curved surfaces, taking into account selected technological and tribological aspects. According to the research conducted by Shan et al. [7], the deformations and forces generated during milling of a thin-walled stainless steel element are strongly related to the inclination of the machined surface. The authors showed that the lowest values of cutting forces and deformations occur when the surface inclination angle is from 15° to 45°. De Oliveira et al. [8], on the other hand, investigated the effect of hydrostatic ball burnishing on the surface quality and ultramicrohardness of the AISI 304 stainless steel (X5CrNi18-10). The research was carried out on flat surfaces.

The results of the burnishing tests showed that the device is characterised by repeatability and stability. The most important parameter was the number of burnishing passes, which reduced the Ra parameter (arithmetic mean deviation [µm]) and the profile amplitude by deforming the roughness peaks resulting from the previous passes. Additionally, the increase in the number of passes enhanced the surface hardness and caused more intense compressive residual stresses. Swiard [9] presented the research on surface roughness after hydrostatic burnishing of the X38CrMoV5-1 steel. The burnishing process parameters taken into account in this study were the burnishing pressure force, burnishing speed and burnishing width. It can be seen that the ball burnishing method using hydrostatic tools is effective in machining the X38CrMoV51 steel elements with a hardness of 48 HRC, provided that the machining parameters are properly selected. The appropriate selection of process parameters, such as pressure, stroke and tool diameter, allows for achieving a favourable geometrical shape of the surface, including, above all, a significant reduction in its roughness. Dzierwa et al. [10] investigated the effect of input process parameters on selected features of the surface layer, such as surface roughness and residual stresses of the 42CrMo4 steel surface after hydrostatic burnishing. It was determined that the ball peening process can serve as a highly effective surface finishing treatment. This process resulted in reduced values of height parameters (Sq, Sz, Sp (maximum peak height [µm]), Sv (maximum pit height [µm])).

The most significant input factor was found to be the burnishing pressure force. The lowest root mean square height (Sq) and maximum height (Sz) were achieved at the highest pressure force. Skoczylas, Zalewski et al. [11] in the paper present the findings of an experimental study on the effects of slide burnishing on surface roughness parameters, topography, surface layer microhardness, and residual stress. In this research, the X6CrNiTi18 stainless steel specimens underwent slide burnishing, with the experimental variables being feed and slide burnishing force. The process resulted in modifications to the surface structure and residual stress distribution, as well as an increase in surface layer microhardness. Post-slide burnishing, the evaluated roughness parameters showed a reduction compared to their values after the initial grinding treatment. In the next article Skoczylas, Zalewski [12] details a study on the effects of different finishing methods on surface topography, surface roughness, surface layer microhardness, residual stresses, and fatigue life. The experiments were conducted using ring samples made of C45 steel. The finishing methods analysed include slide burnishing, ball burnishing, centrifugal shot peening, centrifugal shot peening followed by slide burnishing, and centrifugal shot peening followed by ball burnishing. Results showed that, with the exception of centrifugal shot peening, surface roughness parameters decreased by 59% to 83% compared to the reference surface. When burnishing (either slide or ball) was applied after centrifugal shot peening, surface roughness parameters were further reduced by up to 82% compared to centrifugal shot peening alone. The most significant increase in microhardness was observed with the combination of centrifugal shot peening and slide burnishing, achieving an increase of ΔHV 105 HV 0.05. Zaleski, Skoczylas [13] authors report on a study examining the impact of slide burnishing on the surface roughness, surface layer microhardness, and fatigue life of Ti6Al2Mo2Cr titanium alloy components. Burnishing was carried out using a diamond tip tool with various machining fluids as media. Before burnishing, the samples underwent turning. The process resulted in a significant reduction in surface roughness, with the average roughness (Ra) decreasing by 3.5 times and the roughness (Rz) by 2.5 times. Additionally, there was an increase in surface layer microhardness, with a maximum improvement of 12%, and an enhancement in the fatigue life of the components.

Centrifugal rotary pumps are widely used in ship power plants. They are utilised in cooling circuits of medium and high-power engines, for powering boilers, and in bilge, ballast, and fire protection systems. Pump shafts operating in seawater environments are exposed to corrosion, friction and erosion wear due to difficult operating conditions. Therefore, they are made of corrosion-resistant steel. However, the use of expensive material does not prevent operational damage. Shaft damage includes cracks, plastic deformation, excessive wear of surface in places where rotor discs and stuffing box seals are mounted, corrosion wear, erosive wear and knockout of keyways. In operational practice, excessive wear of the pin surfaces is most often observed, which results in a reduction of their diameter and exceeding the permissible shape deviations. Therefore, it is important that under marine conditions the crew have a solution that will enable the regeneration of a damaged shaft of a machine or ship's power plant device. Ships of the merchant fleet have conventional lathes as equipment in their mechanical workshops. It is important to be able to regenerate machine parts under marine conditions when emergencies occur. Due to the limited possibilities of using any regeneration methods, the process of hydrostatic burnishing of shafts is proposed.

It is worth mentioning that the article authors had prior burnishing experience. In their research on the EN AW-6060 aluminium alloy, they used a single roller multi diameter SRMD device from Yamato. A study was conducted on the impact of burnishing on the surface roughness and hardness of EN AW-6060 aluminium alloy after welding. The results indicated an increase in hardness in the surface layer and an improvement in roughness parameters such as Ra and Rt.

Beneficial changes in the material contribution of the material ratio of the native material and the weld were also observed [14, 15]. The authors' previous experience in pressing using Yamato SRMD single roll multi diameter, allowed them to successfully carry out and interpret the results of the hydrostatic pressing study.

The effect of hydrostatic ball peening on surface roughness was the most frequently analysed feature in the above-mentioned studies. The key factors are force (or pressure), feed and speed, with feed and speed having a particularly significant effect on surface quality.

Many scientific and research centres deal with the subject of surface finishing treatment. The literature review showed that the use of burnishing is used to process different construction materials. The article presents research results which prove that it is possible to use hydrostatic burnishing by the ship's crew to regenerate ship pump shafts in the place of their sealing. This is a new approach to the possibility of using this method in practice.

MATERIALS AND METHOD

The article determines the impact of the hydrostatic burnishing treatment on the quality of the machined surface while strengthening the surface layer of shafts made of the X5CrNi18-10 austenitic steel. The turning process was carried out on a conventional lathe (TUC 50x1000 - Wafum, Wrocław, Poland) shown in Figure 1. In the mechanical processing process, shafts with a diameter of 50 mm were used for the tests. The tested sample was mounted in a three-jaw chuck with support (lathe rotary centre, PZKk SK5). The turning process was carried out using an interchangeable insert designed for machining stainless steel WNMG 080408 MF by Sandvik (Sandvik AB, Stockholm, Sweden). The values of cutting and burnishing speeds and feed were selected based on manufacturer's catalogues and the possibility of setting the spindle speed and feed on the lathe. The recommended cutting parameters according to the manufacturer are depth of cut ap = 0.4 (0.1 ÷ 0.5) mm, feed rate f = 0.2 (0.1 ÷ 0.4) mm/rev, and cutting speed Vc = 240 m/min for steel hardness HB = 180.

In the turning process, the first pass of the cutting tool was intended to remove runout and align of the shaft. The finishing turning process was carried out with a ap = 1 mm. The remaining cutting parameters are of f = 0.24 mm/rev and Vc = 109 m/min. Machining was carried out dry, without the use of lubricating or cooling liquid. Figure 2 shows a view of the holder – shaft-cutting tool.

The machining of the hydrostatic burnishing process was carried out on the same conventional lathe. In the surface plastic treatment process, a hydrostatic burnisher tool by Ecoroll was used (Ecoroll AG Werkzeugtechnik, Celle, Germany). Figure 3 shows the shaft after finishing turning and burnishing process, as well as the burnishing tool.

On the basis of technological documentation and own research, the technological parameters of the burnishing process were selected. [16, 17]. The shaping of the surface layer of the shaft was carried out with a feed of fn = 0.08 mm/rev and a burnishing speed of Vn = 42 m/min. The burnishing ball pressure was achieved by regulating the pressure of the cooling and lubricating liquid from the hydraulic pump. The range of pressures used was from 50 ÷ 300 bar, which corresponds

Figure 1. The view of a conventional lathe

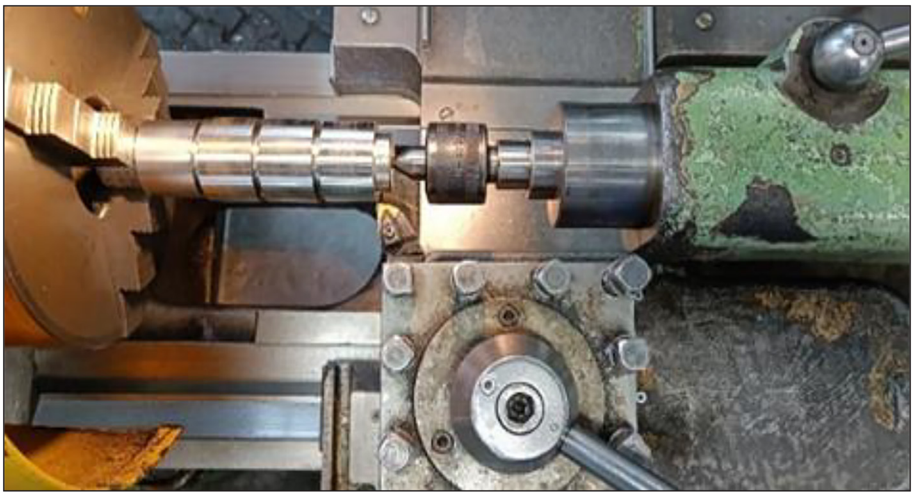

Figure 2. View of mounting the shaft and cutting tool on a TUC 50x1000 lathe

Figure 3. View of a hydrostatic burnishing tool and shaft on a lathe

to the burnishing force range from 500 ÷ 3000 N. The pressure was adjusted every 50 bar.

Before performing surface roughness measurements, the directionality of the profile structure must be determined. The type of machining applied to a given surface is characteristic of their individual types. Therefore, an important issue is the assessment of the surface after treatment, which allows the correct determination of the elementary cross-section. The measurement with a profilometer was made along the rolling axis so that the analysed parameters reached maximum values. The measurement was performed in a direction perpendicular to the surface structure irregularities.

Figure 4 shows the shaft after finishing processing and the W20 profilometer by JENOPTIK, which was used to measure surface roughness and material ratio. The tests of the analysed surface parameters were carried out on a measuring section of 4.0 mm (ln parameter) (measuring section [mm]), for which an elementary section of 0.8 mm (lr parameter – elementary section [mm]) was selected. Measurements were carried out at a speed of Vt = 0.5 mm/s (Vt – measurement speed [mm/s]). The induction head with the measuring stylus tip is 2 μm.

The impact of hydrostatic burnishing process was determined on the basis of selected parameters of roughness and material ratio of the surface: Ra [μm] – arithmetic mean deviation, Rt [μm] – total height of profile, Rk [μm] – core roughness depth, Rpk [μm] – reduced peak height, Rpv [μm] – reduced valley depth.

The indices of surface roughness reduction and material ratio were used for analyse the influence of the burnishing treatment on the obtained measurement results. The formula 1 shows the reduction index for the roughness parameter Ra. The other indices (KRa, KRt, KRk, KRpk, KRvk)

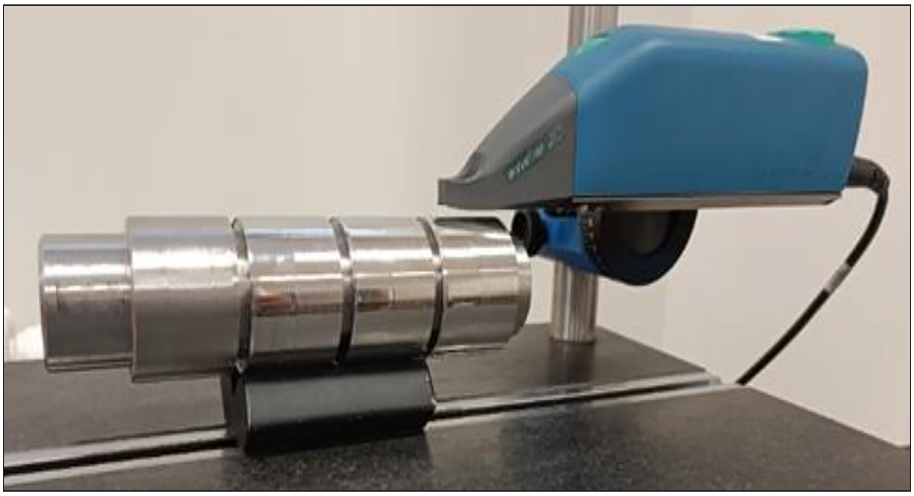

Figure 4. View of the W20 profilometer and the tested workpiece

– material ratio reduction indices [-], were calculated according to the same rules.

$$K_{Ra} = \frac{Ra_2}{Ra_1} \quad (1)$$

where: *KRa* – surface roughness reduction index for the *Ra* parameter, Ra_2 – surface roughness parameter after burnishing [μm], Ra_1 – surface roughness parameter after turning [μm].

A universal hardness tester Qness 250M was used to test of the surface hardness (Figure 5a). Figure 5b shows a view from the hardness measurement test performed using the Vickers *HV*10 method. Relative surface hardening index *KSu* [%] determining the influence of the applied surface plastic treatment on the hardening of the surface layer (2).

$$KSu = \frac{HV_2 - HV_1}{HV_1} \cdot 100\% \quad (2)$$

where: *KSu* – index of relative surface strengthening, HV_1 – material hardness before burnishing, HV_2 – material hardness after burnishing.

RESEARCH RESULTS

After the finishing turning process, clear machining traces in the form of scratches can be seen on the surface of the shafts. Visible surface scratches are the result of the use of reduced cutting speed and the lack of use of a cooling and lubricant. Cutting inserts are designed for high-performance machining, and conventional lathes are often unable to set such high spindle speeds. The lack of liquid use in the cutting process was intended to additionally worsen the cutting conditions in order to better determine the benefits of using hydrodynamic burnishing.

Finishing processes were carried out with one workpiece clamping on the machine tool. An example view of the shaft surface after finishing turning is shown in Figure 6a. Figure 6b presents a view of the shaft, on which the turning process was carried out, and then half of the shaft was subjected to the burnishing process.

Measurements of the parameters of surface roughness, surface hardness and material ratio were performed at five measurement points, while 3 measurements were qualified for statistical analysis. Extreme values were rejected.

Table 1 presents the results of the statistical analysis of the Ra parameter and KRa index. The average values of the analysed parameter after finishing turning were below 1 μm, with the exception of the shaft pin (Ra = 1.64 μm), for which the ball pressure on the processed surface of 250 bar was used.

Burnishing treatment using the lowest pressure value (50 bar) allowed obtaining a surface with KRa = 5.1. Increasing the pressure value above 100 bar allowed obtaining a surface with a Ra parameter value below 0.1 μm. The lowest average values of the parameter Ra = 0.05 μm were obtained in the range of ball pressure on the processed surface in the range of 200–300 bar. For

a) b)

Figure 5. Hardness measurement (a) hardness tester (b) measurement result

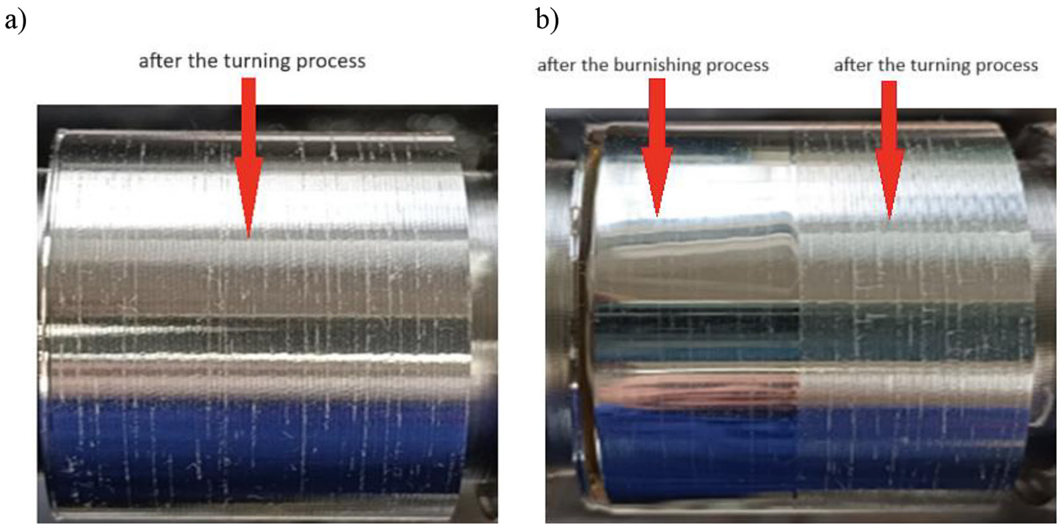

Figure 6. An example view of the shaft surface (a) after the finishing turning process and (b) after the turning and burnishing process

these shaft pins, the KRa index values were more than two or three times higher, and the highest value of 32.8 was obtained on the shaft pin surface with a pressure of 250 bar. The largest machining defects were created on the surface of this shaft pin after the turning process, which resulted in a high average value of the Ra parameter. An example measurement view is shown in Figure 7.

Figure 8 shows a graphical interpretation of the results of the impact of the analysed machining on the change in the average value of the Ra parameter for pins.

Table 2 presents the results of the statistical analysis of the Rt parameter and KRt index. Figure 9 shows their graphical interpretation. The use of surface plastic processing had a positive effect on the obtained measurement results. As the pressure increases in the range from 50 to 200 bar, the KRa index value increases. The greatest increase in the analysed parameter was obtained for the process with a pressure of 250 bar (KRa = 37.1). The highest pressure of the ball on the surface allowed obtaining a KRa index of 9.8.

Measurements of parameters Ra and Rt presented that the applied hydrostatic burnishing process has a positive effect on improving the quality of the machined surface. The highest values of the coefficients KRa = 32.8 μm and KRt = 37.1 were obtained for the shaft surface subjected to ball pressure of 250 bar.

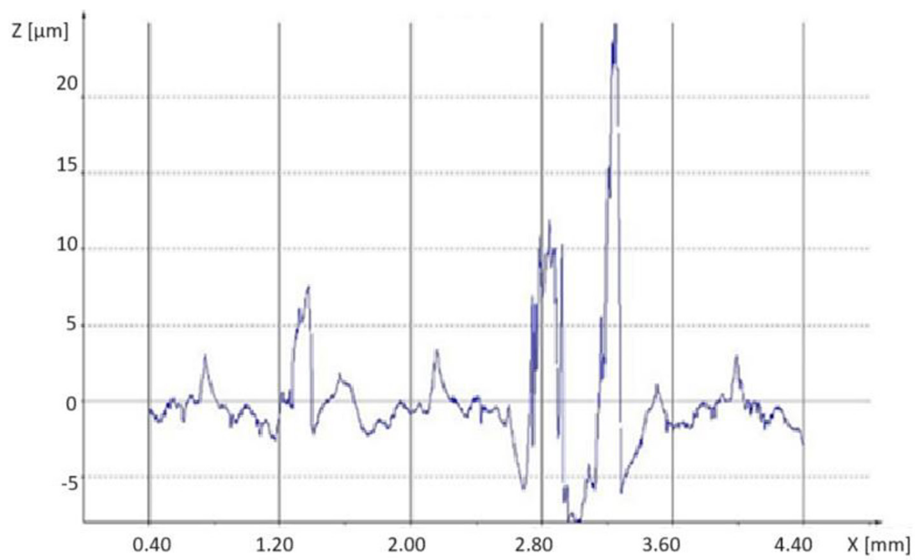

Figure 7. View of the profilogram from an example measurement

Table 1. Results of analysis of Ra parameter and KRa index

Pressure [bar]	Basic statistical analysis	*Ra [μm]*		*KRa [-]*
		After turning	After burnishing	
50	Mean	0.76	0.15	5.1
	Stand.dev.	0.11	0.04	
	Stand.error	0.07	0.02	
	Minimum	0.63	0.11	
	Maximum	0.85	0.18	
100	Mean	0.98	0.08	12.3
	Stand.dev.	0.30	0.01	
	Stand.error	0.17	0.00	
	Minimum	0.67	0.07	
	Maximum	1.27	0.08	
150	Mean	0.90	0.06	15.0
	Stand.dev.	0.19	0.02	
	Stand.error	0.11	0.01	
	Minimum	0.69	0.05	
	Maximum	1.06	0.08	
200	Mean	0.74	0.05	14.8
	Stand.dev.	0.11	0.00	
	Stand.error	0.06	0.00	
	Minimum	0.61	0.05	
	Maximum	0.81	0.05	
250	Mean	1.64	0.05	32.8
	Stand.dev.	0.46	0.01	
	Stand.error	0.27	0.00	
	Minimum	1.32	0.04	
	Maximum	2.17	0.05	
300	Mean	0.94	0.05	18.8
	Stand.dev.	0.33	0.02	
	Stand.error	0.19	0.01	
	Minimum	0.72	0.04	
	Maximum	1.32	0.07	

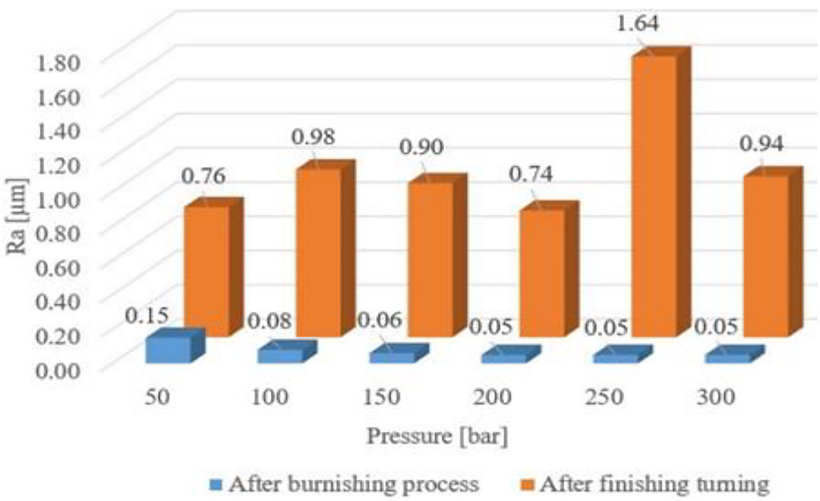

Figure 8. Change of the Ra parameter after burnishing process

Table 2. Results of analysis of *Rt* parameter and *KRt* index

Pressure [bar]	Basic statistical analysis	*Rt [μm]*		*KRt [-]*
		After turning	After burnishing	
50	Mean	6.66	2.63	2.5
	Stand.dev.	2.60	1.21	
	Stand.error	1.50	0.70	
	Minimum	5.01	1.41	
	Maximum	9.66	3.82	
100	Mean	11.38	2.00	5.7
	Stand.dev.	6.91	1.13	
	Stand.error	3.99	0.65	
	Minimum	5.02	1.29	
	Maximum	18.74	3.30	
150	Mean	10.49	1.36	7.7
	Stand.dev.	4.77	0.44	
	Stand.error	2.76	0.25	
	Minimum	5.10	1.04	
	Maximum	14.17	1.86	
200	Mean	6.54	0.58	11.3
	Stand.dev.	0.98	0.11	
	Stand.error	0.57	0.06	
	Minimum	5.51	0.48	
	Maximum	7.46	0.70	
250	Mean	23.03	0.62	37.1
	Stand.dev.	8.91	0.15	
	Stand.error	5.15	0.09	
	Minimum	15.57	0.45	
	Maximum	32.90	0.71	
300	Mean	9.90	1.01	9.8
	Stand.dev.	5.31	0.70	
	Stand.error	3.06	0.40	
	Minimum	5.62	0.45	
	Maximum	15.84	1.79	

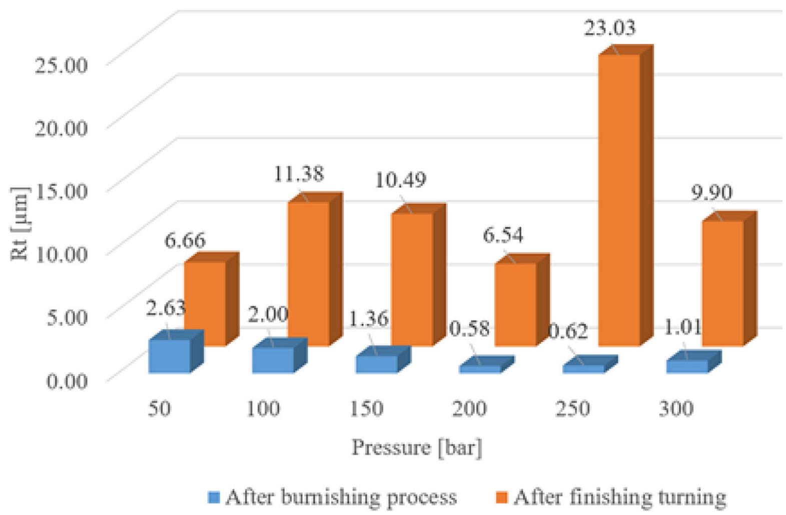

Figure 9. Change of the Rt parameter after burnishing process

In order to better determine the impact of the burnishing treatment used on the quality of the machined surface, the material ratio parameters were analysed. Table 3 presents the results of the statistical analysis of the Rk parameter and KRk index. The burnishing process will have a positive effect on the load-bearing capacity of the surface in the entire range of pressures applied to the surface of the shaft pins. The greatest value of the KRk index was obtained after machining the shaft with a pressure of 250 bar. A graphical interpretation of the results obtained for the Rk parameter is shown in Figure 10.

Table 4 shown the results of the statistical analysis of the Rpk parameter and the KRpk index. Table 5 presents the results of the statistical analysis of the Rvk parameter and the KRvk index. The highest values of the KRpk and KRvk index were also obtained for the shaft pin with a pressure of 250 bar. The value of KRpk = 93.1 proves the significant impact of the burnishing tool on levelling individual surface scratches resulting from finishing turning. The peaks of the surface irregularities were pressed into the valleys and significantly reduced the Rvk parameter. A graphical interpretation of the results for the Rpk and Rvk parameters is presented in Figures 11 and 12.

Figure 13 shows the impact of the surface plastic treatment on the material ratio curve. The course of the curve presented in Figure 13b confirms the beneficial effect of the applied finishing treatment of the shaft journals, compared to the curve

Table 3. Results of analysis of Rk parameter and KRk index

Pressure [bar]	Basic statistical analysis	*Rk [µm]*		*KRk [-]*
		After turning	After burnishing	
50	Mean	2.61	0.43	6.1
	Stand.dev.	0.40	0.10	
	Stand.error	0.23	0.06	
	Minimum	2.16	0.32	
	Maximum	2.91	0.52	
100	Mean	2.87	0.24	12.0
	Stand.dev.	0.58	0.03	
	Stand.error	0.33	0.02	
	Minimum	2.24	0.20	
	Maximum	3.38	0.26	
150	Mean	2.83	0.24	11.8
	Stand.dev.	0.54	0.06	
	Stand.error	0.31	0.03	
	Minimum	2.21	0.19	
	Maximum	3.21	0.30	
200	Mean	2.35	0.21	11.2
	Stand.dev.	0.22	0.02	
	Stand.error	0.13	0.01	
	Minimum	2.11	0.19	
	Maximum	2.54	0.22	
250	Mean	3.63	0.17	21.4
	Stand.dev.	0.45	0.02	
	Stand.error	0.26	0.01	
	Minimum	3.13	0.16	
	Maximum	4.01	0.19	
300	Mean	2.65	0.17	15.6
	Stand.dev.	0.70	0.04	
	Stand.error	0.41	0.02	
	Minimum	1.99	0.14	
	Maximum	3.39	0.21	

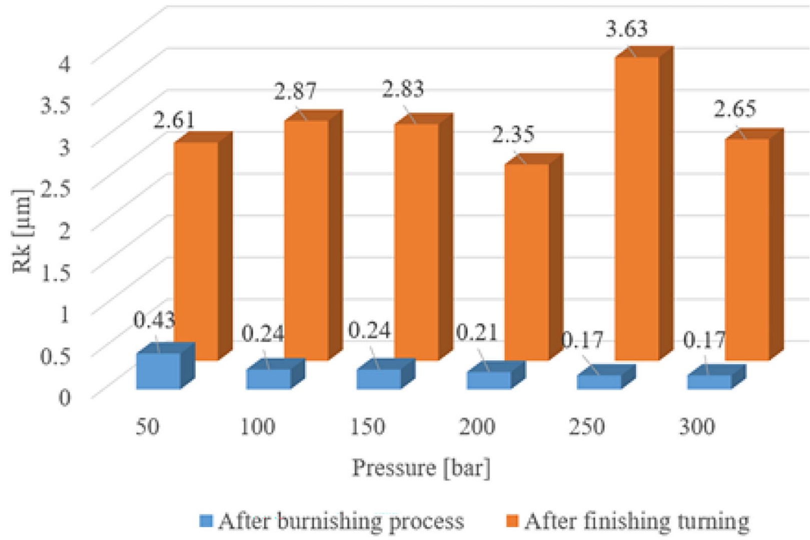

Figure 10. Change of the Rk parameter after burnishing process

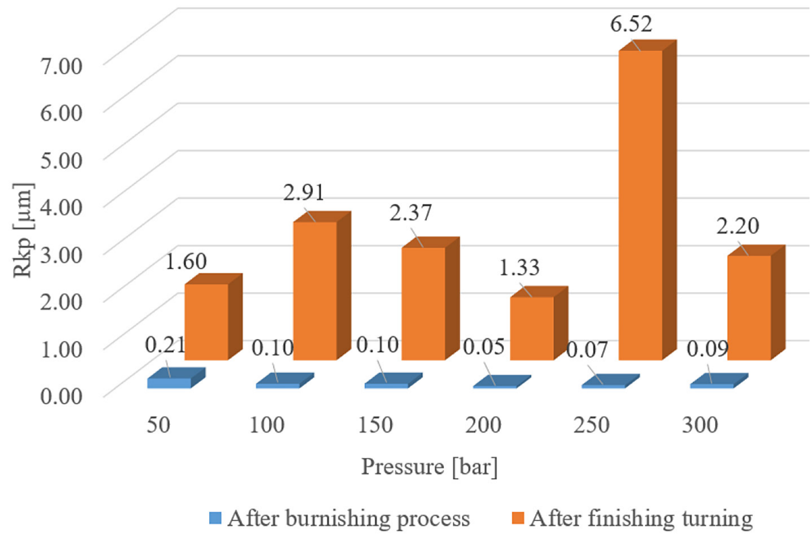

Figure 11. Change of the Rpk parameter after burnishing process

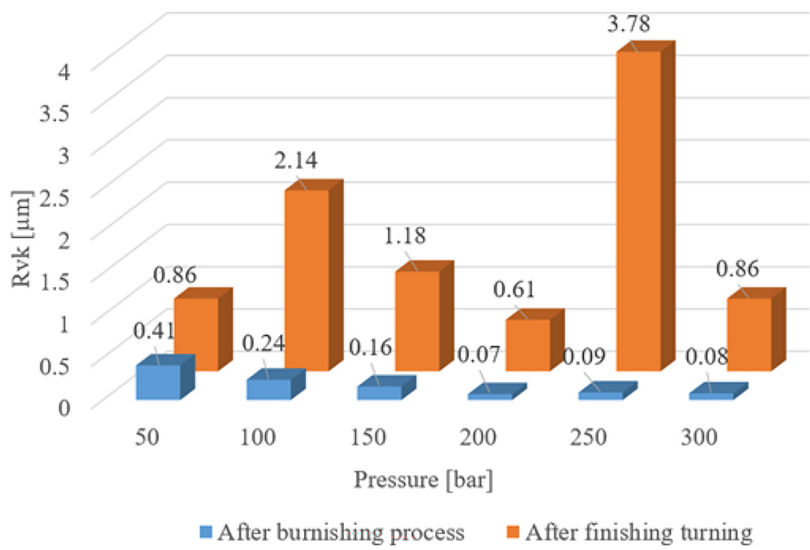

Figure 12. Change of the Rvk parameter after burnishing process

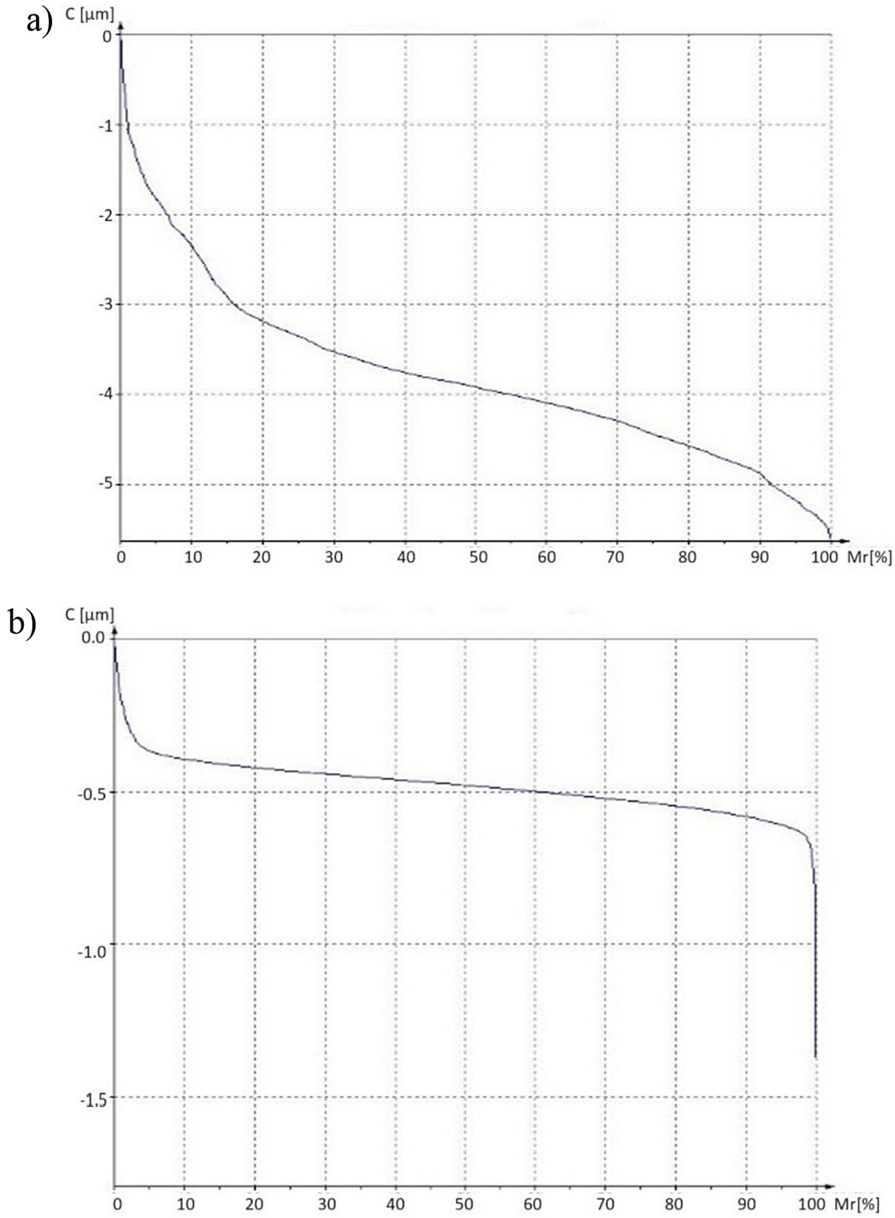

Figure 13. An example photo of the material ratio curve a) after finishing turning b) after burnishing

Figure 13a. The burnishing tool evened the surface of the shaft journal by reducing the peaks of surface irregularities and filling the profile recesses.

Surface hardness measurements and index KSu after the finishing treatment are presented in Table 6. A graphical interpretation of the results is shown in Figure 14. Burnishing treatment resulted in an increase in surface hardness for the all range of ball pressure applied to the processed shaft journal. At values of 50 and 100 bar, surface hardness index equal 26% and 34% were achieved. The use of pressure above 150 bar showed Su index of over 50%. From the point of view of finishing operations in which burnishing is used, it is important not to exceed the maximum burnishing forces on the surface of the shafts. Too much tool pressure on the processed surface may cause the material to peel. This is an undesirable phenomenon that was not noticed in the studies conducted.

CONCLUSIONS

The article presents the results of research on the influence of hydrostatic burnishing treatment on the parameters of surface roughness, material ratio and strengthening of the surface layer. The use of such a surface finishing process by the ship's crew during the cruise is an element of the novelty of the conducted research. This process

Table 4. Results of analysis of Rpk parameter and KRpk index

Pressure [bar]	Basic statistical analysis	*Rpk [μm]*		*KRpk [-]*
		After turning	After burnishing	
50	Mean	1.60	0.21	7.6
	Stand.dev.	0.74	0.10	
	Stand.error	0.43	0.06	
	Minimum	1.17	0.11	
	Maximum	2.46	0.31	
100	Mean	2.91	0.10	29.1
	Stand.dev.	1.28	0.04	
	Stand.error	0.74	0.02	
	Minimum	1.46	0.05	
	Maximum	3.90	0.12	
150	Mean	2.37	0.10	23.7
	Stand.dev.	0.82	0.04	
	Stand.error	0.47	0.02	
	Minimum	1.61	0.07	
	Maximum	3.23	0.14	
200	Mean	1.33	0.05	26.6
	Stand.dev.	0.24	0.01	
	Stand.error	0.14	0.01	
	Minimum	1.11	0.04	
	Maximum	1.59	0.06	
250	Mean	6.52	0.07	93.1
	Stand.dev.	2.42	0.03	
	Stand.error	1.40	0.02	
	Minimum	4.01	0.04	
	Maximum	8.84	0.10	
300	Mean	2.20	0.09	24.4
	Stand.dev.	0.69	0.05	
	Stand.error	0.40	0.03	
	Minimum	1.68	0.04	
	Maximum	2.99	0.14	

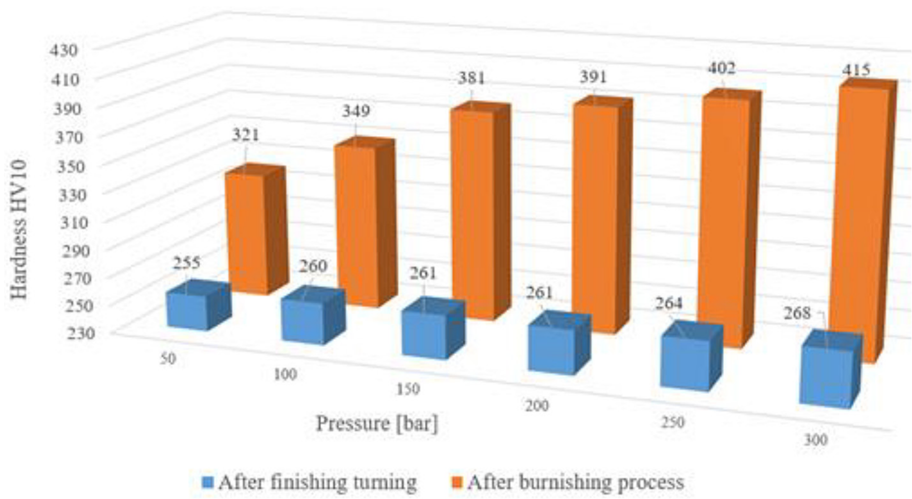

Figure 14. Change of the surface hardness after burnishing process

Table 5. Results of analysis of Rvk parameter and KRvk index

Pressure [bar]	Basic statistical analysis	*Rvk [µm]*		*KRvk [-]*
		After turning	After burnishing	
50	Mean	0.86	0.41	2.1
	Stand.dev.	0.20	0.21	
	Stand.error	0.11	0.12	
	Minimum	0.72	0.17	
	Maximum	1.09	0.53	
100	Mean	2.14	0.24	8.9
	Stand.dev.	2.73	0.15	
	Stand.error	1.58	0.08	
	Minimum	0.48	0.14	
	Maximum	5.29	0.41	
150	Mean	1.18	0.16	7.4
	Stand.dev.	0.97	0.11	
	Stand.error	0.56	0.07	
	Minimum	0.48	0.09	
	Maximum	2.28	0.29	
200	Mean	0.61	0.07	8.7
	Stand.dev.	0.42	0.01	
	Stand.error	0.24	0.01	
	Minimum	0.17	0.06	
	Maximum	1.01	0.08	
250	Mean	3.78	0.09	42.0
	Stand.dev.	3.48	0.04	
	Stand.error	2.01	0.02	
	Minimum	1.35	0.05	
	Maximum	7.77	0.13	
300	Mean	0.86	0.08	10.8
	Stand.dev.	0.37	0.02	
	Stand.error	0.22	0.01	
	Minimum	0.44	0.07	
	Maximum	1.16	0.10	

would enable obtaining a surface with particularly favorable properties during the regeneration of shaft pins in the place of their sealing. On the basis of the obtained research results, the following conclusions can be formulated:

1. The tests carried out showed that the burnishing treatment used allows obtaining surfaces with Ra parameter values below 0.15 µm for the test with the lowest ball pressure of 50 bar. Increasing the burnishing force allowed obtaining surfaces with lower average values of the Ra parameter, up to obtaining a surface with Ra = 0.05 µm. For burnishing process with ball pressure of 150 and 200 bar, a 15 times decrease of the Ra parameter value was achieved. The greatest reduction in the Ra parameter was achieved on the shaft journal, where the process was carried out at a pressure of 250 bar. A nearly 33 times decrease in value was achieved.
2. From the point of view of the regeneration of shafts for seals, it is important to achieve a significant reduction in the value of the Rt parameter. This is achieved by smoothing the peaks of surface irregularities with a burnishing ball. A 37 times reduction in the Rt parameter was observed for a ball pressure of 250 bar. For the burnishing process at a pressure of 200 and 300 bar, the KRt index equal 11.3 and 9.8, respectively, was obtained.

Table 6. Results of analysis of surface hardness measurement and KSu index

Pressure [bar]	Basic statistical analysis	*HV10*		*KSu [%]*
		After turning	After burnishing	
50	Mean	255	321	26
	Stand.dev.	7.6	0.6	
	Stand.error	4.4	0.3	
	Minimum	247	321	
	Maximum	262	322	
100	Mean	260	349	34
	Stand.dev.	4.6	4.4	
	Stand.error	2.6	2.5	
	Minimum	255	346	
	Maximum	264	354	
150	Mean	261	381	46
	Stand.dev.	3.2	1.2	
	Stand.error	1.9	0.7	
	Minimum	259	380	
	Maximum	265	382	
200	Mean	261	391	50
	Stand.dev.	3.8	3.2	
	Stand.error	2.2	1.9	
	Minimum	257	389	
	Maximum	264	395	
250	Mean	264	402	52
	Stand.dev.	1.5	2.5	
	Stand.error	0.9	1.5	
	Minimum	263	400	
	Maximum	266	405	
300	Mean	268	415	55
	Stand.dev.	3.0	2.1	
	Stand.error	1.7	1.2	
	Minimum	265	413	
	Maximum	271	417	

3. Moreover, the obtained values of the analysed material ratio parameters also prove the beneficial effect of the use of hydrostatic burnishing treatment. In the all range of analyzed pressures on the shaft surface, a decrease in parameters and indicators relating to the material ratio was observed. The greatest values of the indices KRk = 21.4, KRpk = 93.1 and KRkv = 42 were obtained for the shaft pin subjected to the burnishing process with a pressure of 250 bar.
4. The use of hydrostatic burnishing process also resulted in benefits in relation to the strengthening of the surface layer of the shaft surface. The surface plastic processing of the shaft pin resulted in an increase in the hardness of the material by 26% at the lowest pressure value. However, the greatest increase in surface hardness (Su = 55%) was obtained for a pressure of 300 bar.
5. On the shaft pins, where the burnishing process was applied under a pressure of 250 bar, a significant impact of the finishing turning treatment can be seen. Constant cutting parameters do not ensure repeatability of the obtained surface quality in relation to other processed shaft pins. Therefore, the use of hydrostatic burnishing as an additional finishing treatment is a good solution, which allows obtaining surfaces with more approving parameters of surface

Table 6. Results of analysis of surface hardness measurement and KSu index

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	Stand.error	1.7	1.2	
	Minimum	265	413	
	Maximum	271	417	

roughness and material content, as well as with increased surface hardness.

During the burnishing process, the peaks of surface irregularities undergo plastic deformation under the influence of the burnishing tool. Therefore, reducing the values of the analysed parameters of surface roughness and material ratio, while strengthening the surface layer, should have a positive impact on the improvement of selected operational properties of shaft pins. In marine conditions, burnishing can be used to regenerate shaft pins, which allows for improved surface quality while strengthening the surface layer. Hydrostatic burnishing can be used to regenerate shafts at the seal location. Further research is planned on the operational properties of stainless steel shaft sleeves dedicated to naval pumps.

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