MULTI-CRITERIA OPTIMIZATION OF STEEL BURNISHING PARAMETERS APPLIED TO MARINE PUMPS SHAFT PINS

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Abstract

The paper presents the research results of the possibilities of applying burnishing as steel finishing treatment for marine pumps shafts. X5CrNi1810 (AISI 304 L) corrosion resistant steel in the form of a roller 40 mm in diameter was used for the research. The burnishing process was carried out by SRMD single roll burnish by Yamato. During the process of burnishing various parameters of the technological process were used, that is burnishing force, speed and feed.

Within the research, the optimization of burnishing technological parameters was conducted on account of the minimalization of R_a coefficient as well as the maximalization of S_u. The S_u coefficients values determining the degree of relative hardness of surface layer varied depending on the burnishing parameters applied and fluctuated around 1% to 18%. However, the values of K_{Ra} coefficients defining the surface roughness reduction index were in the range of 1 to 15 as a result of burnishing. The object of the paper was to determine the optimal burnishing parameters in order to achieve the highest level of surface layer relative hardness and to decrease the surface roughness of marine pumps shaft pins made of stainless steel. The multi-criteria optimization conducted with the use of min-max method demonstrated that with regard to maximum surface hardness level, burnishing should be carried out at the following parameters of the technological process: burnishing force 1.1 kN, burnishing speed 35 m/min and feed 0.13 mm/rev.

***Keywords**: multi-criteria optimization, burnishing, stainless steel, surface layer, angular momentum pumps*

1. Introduction

Technology used in production process has a vital influence on the reliability and service life of machine parts. The final formation of surface layer, that is the dimensions and service properties, is achieved during finish treatment of a given element [1, 2]. The burnishing method has been known for several dozen years. The first tools for burnishing holes were made in 1960-1965 and some years later the ones for burnishing rolls. The basic aim of burnish treatment is the achievement of suitable properties of surface layer, which have a considerable influence on the durability of machine elements.

Burnishing technology can be used in machinery industry plants. It allows eliminating traditional finish machining such as: grinding, super finishing, honing and polishing. Therefore the final formation of dimensions and service properties by means of burnishing becomes a chipless and dustless treatment which qualifies burnishing for ecological treatment method [4]. In industrial experience this process is carried out on universal machine tools as well as on CNC machine tool but belongs to plastic tooling. The review of literature pointed out three fundamental purposes of the application of burnishing in the machine elements production process;

- smoothness tooling – which reduces the surface roughness after machining that precedes burnishing,
- strengthening tooling – which increases service properties (i.e. resistance to fatigue wear, abrasive wear and corrosive wear) by the change of material properties in the surface layer,
- dimension-smoothness tooling – which increases the dimension accuracy and simultaneously reduces surface roughness to its required value.

Burnishing process enables surface working at high dimensional precision (accuracy class 7 and 6) which leads to the following advantages [3]:

- ability to reach high surface smoothness (R_a = 0.32-0.04 μm) and high bearing surface of roughness profile (90%),
- increasing the surface hardness,
- increasing resistance to fatigue (both surface and volumetric),
- increasing resistance to abrasive and mashing wear,
- lack of abrasive grit, sharp and hard built-up edge fragments and chips on burnished surface,
- possibility of using burnish tools on universal lathes (the concept of one stand working),
- eliminating or limiting the time consuming operations such as: honing, lapping, grinding and polishing,
- ability to eliminate heat treatment in specific cases,
- high process efficiency (one working transition of a tool) and production costs,
- reduction high durability of burnishes,
- reducing expenses relating to machine parts production.

Numerous scientific centres all over the world deal with burnishing treatment and its impact on the surface layer [6, 9]. Research programmes usually cover issues related to burnishing of cast iron [7], some heat resisting alloys, stainless steel, copper alloys and aluminium [10], titanium and its alloys [8, 11], galvanic ,diffusive and padded coatings [3], as well as parts produced by sintering metal powders.

On account of so many advantages resulting from burnishing treatment, it is believed that a determination of burnishing optimal parameters can be proposed in order to obtain the highest relative hardness of surface layer and to reduce surface roughness of shaft pins in marine angular momentum pumps made of X5CrNi1810 stainless steel. That is why a multi-criteria optimization based on min-max method was applied.

2. Samples preparation

The rollers of X5CrNi1810 stainless steel were preliminarily machined so as to prepare the shaft pins for burnishing. The process of turning was carried out on TUC 40lathe (Fig. 1) by a cutting tool with WNMG 080408 WF removable plates by Sandvik Coromant. During turning the following machining parameters were applied: machining speed V_c = 112 m/min, rate of feed f = 0.27 mm/rev and machining depth a_p = 0.5 mm.

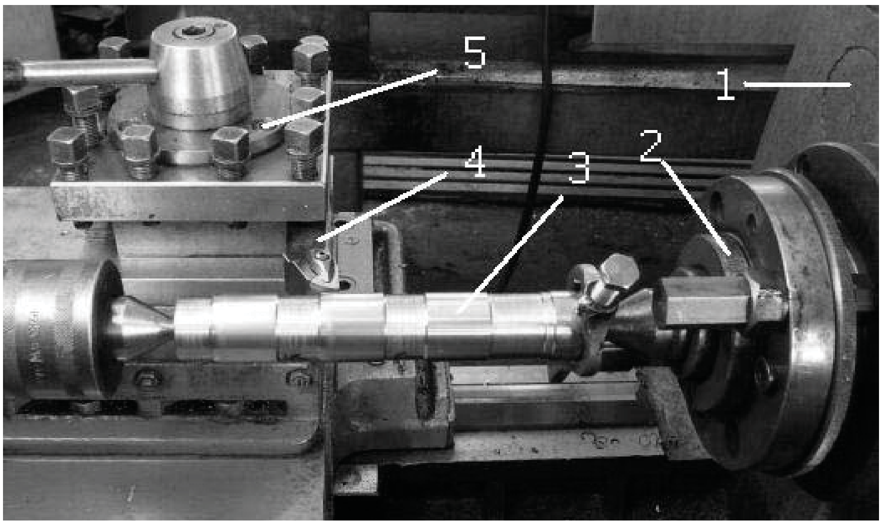

Fig. 1. General view of OUPN tooling system (machine, grip, object, tool): 1 – TUC40 lathe, 2 – catch plate, 3 – work piece object, 4 – cutting tool, 5 – tool post

In spite of the fact that fixed technological parameters were applied for machining, various results were achieved for surface roughness measurements of the rollers examined. The average arithmetic roughness profile deviation varied from 0.5 to 1.18 μm. The average value of R_a roughness factor was 0.83 μm (Tab. 1). The average hardness after turning was 307 HV and the basic statistic analysis results are shown in Tab. 2.

Tab. 1. The results of statistic analysis of roughness factor measurements (measurements number 48)

Mean	Median	Minimum	Maximum	Stand. Dev.	Stand. Error
0.83	0.79	0.50	1.18	0.14	0.02

Tab. 2. The results of statistic analysis of hardness measurements (measurements number 48)

Mean	Median	Minimum	Maximum	Stand. Dev.	Stand. Error
307	307	284	325	8.75	1.26

3. Research methodology

The process of burnishing was conducted by SRMD one roll burnish by Yamato (Fig. 2). Shaft pins made of X5CrNi1810 stainless steel of the diameter ϕ39 mm were burnished. The technological process parameters applied for surface plastic treatment are shown in Tab. 3.

Fig. 2. Burnishing tool

Tab. 3. Technological parameters of burnishing process

Parameter		Values
Burnishing force – F	[kN]	0.7, 0.9, 1.1
Burnishing speed – V_n	[m/min]	35, 56, 88, 112
Feed – f	[mm/rev]	0.13, 0.54, 0.94, 1.2

The hardness test was carried out by means of Vickers method with the use of WPM device, at thrust force amounting to 50 N. On the basis of the results achieved the degree of S_U surface layer relative hardness was determined:

$$S_U = \frac{HV_2 - HV_1}{HV_1} \cdot 100\% , \tag{1}$$

where:
S_U - degree of surface layer relative hardness,
HV_1 - material hardness before burnishing,
HV_2 - material hardness after surface plastic treatment.

The surface roughness was measured by HOMMEL TESTER T 1000 profile meter. The measuring length of test sample amounted to 4.8 mm, while the sampling length was 0.8 mm. On the basis of the results achieved, the K_{Ra} surface roughness reduction factor was defined.

$$K_{Ra} = \frac{R_a'}{R_a}, \tag{2}$$

where:
K_{Ra} - surface roughness reduction factor
R_a' - material surface roughness,
R_a - material surface roughness after surface plastic treatment.

The results defining surface hardness and roughness underwent statistic analysis of multiple regression in order to determine their influence on properties examined. The calculations were conducted with the help of Statistica 5.5 computer program. Due to different independent variables, the influence of particular parameters was analyzed on the basis of standardized regression factors (BETA).

The multi-criteria optymalization was carried out by min-max method, which is based on the minimalization of maximum deviations from optimum values for all functions of optimization criterion. Relative deviations from the extreme solutions are defined for each *i*-th criterion function by formulas 3 and 4:

$$\Delta_i'(x) = \frac{|f_i(x) - F_i^\circ|}{|F_i^\circ|}, \tag{3}$$

$$\Delta_i''(x) = \frac{|f_i(x) - F_i^\circ|}{|f_i(x)|} \tag{4}$$

for $F_i^\circ \neq 0$ and $f_i(x) \neq 0$ which define relative increment of a dependent variable for minimalized objective function, and also define relative drop of the same dependent variables for maximum functions [5].

The method mentioned above seeks parameters values whose particular objective functions give resulting parameter values which are equally and the least possibly distant from the extremes of both objective functions (formula 5), that is such values for which the increments and drops of both objective functions are identical and possibly low.

$$\Lambda_{i \in I}\left(\Delta_i(x) = \max\langle w_i \Delta_i'(x), w_i \Delta_i''(x)\rangle\right), \tag{5}$$

where:
i - the amount of objective functions,
w_i - weight coefficient of *i*-th objective function, where $0 < w_i \leq 1$.

4. Research results

Burnishing parameters applied in the research influenced both the reduction of surface roughness index and the increase of surface layer hardness of the material treated. The S_u coefficients values defining the degree of surface layer relative hardness were changing according to burnishing parameters applied and fluctuated within 1% to 18%. Analyzing the impact of burnishing parameters on the degree of surface layer relative hardness, the multiple regression analysis was used. The analysis showed that the burnishing speed has the greatest influence on S_u hardness coefficient and with its increase the decrease of the material relative hardness degree takes place. The burnishing force has a lower influence on S_u coefficient but with its increase the material hardness occurs. The feed has the lowest influence on the value of S_u coefficient and it is statistically irrelevant [12].

Final values of standard regression coefficients (BETA), coefficients (B), and significance levels (p levels) of the multiple regression analysis that was carried out without taking feed into account were presented in Tab. 4. The remaining coefficients take constant values and are respectively: correlation coefficient $R = 0.81$, determination coefficient $R^2 = 0.65$, $F(2.45) = 42.175$, $p < .00000$ estimation error: 2.42. Formula 6 shows the achievement of multiple regression equation for S_u parameter.

Tab. 4. The results of S_u parameter statistic analysis for variables presented in Tab. 3 without taking into account the feed

	BETA	B	p level
Free term		12.05	0.00
Burnishing speed – V_n	-0.79	-0.11	0.00
Burnishing force – F	0.18	0.004	0.04
Multiple regression equation: $S_u = 0.004F - 0.11V_n + 12.05$			

As a result of burnishing that was carried out the values of K_{Ra} variable defining the surface roughness decrease factor ranged from 1 to 15. Analyzing the influence of burnishing variables on the surface roughness factor the multiple regression analysis was also used. When examining the values of standardized multiple regression coefficients obtained for independent variables it is possible to state that feed has the greatest impact on K_{Ra} surface roughness reduction index. The lower the feed value used for burnishing operation, the lower the value of mean arithmetic deviation of R_a roughness profile. The second significant variable affecting the quality of the surface achieved and consequently the K_{Ra} factor is the burnishing force. The increase of burnishing force results in the decrease of R_a parameter value. Further analysis indicated that V_n variable is statistically irrelevant for the parameter defining the stereo metric structure of shaft pins. Finding the logarithm of feed and K_{Ra} variables was conducted in order to improve matching of the multiple regression equation to the measurements results obtained in the research [12].

The final coefficient values BETA, B, and p level were shown in Tab. 5. The BETA, B, and p level values obtained were given in Tab. 5 while the remaining coefficients take constant values and are respectively: correlation coefficient $R = 0.83$, determination coefficient $R^2 = 0.70$, $F(2.45) = 51.377$, $p<.00000$ and estimation error: 0.17. Formula 7 shows the multiple regression equation for K_{Ra} variable.

Tab. 5. The results of K_{Ra} parameter statistic analysis for variables presented in table 3 without taking into account the burnishing speed

	BETA	B	p level
Free term		-0.64	0.00
Burnishing force – F	0.52	0.001	0.00
Feed – log f	-0.65	-0.51	0.00
Multiple regression equation: $\log K_{Ra} = 0.001F - 0.51\text{og } f - 0.64$			

Shaft pins burnishing resulted in obtaining high smoothness of a surface as well as surface layer hardening. Input factors, which influence the effects of an examined process are the burnishing force, feed and burnishing speed. In the optimization process, the input variables values were defined with regard to both parameters at the same time, assuming their identical weights. That is why the technological process aiming at reaching low roughness value should be performed with the greatest burnishing force possible and the smallest feed. However, in order to obtain high coefficient of surface layer relative hardness degree, the technological process should be conducted

Tab. 6. Compromise solutions

Lp.	F [N]	f [mm/rev]	V_n [m/min]	K_{Ra}	S_U	$\Delta' K_{Ra}$	$\Delta'' K_{Ra}$	$\Delta' S_U$	$\Delta'' S_U$
1	720	0.13	35	3.4	11.5	0.6198	1.6303	0.1272	0.1457
2	720	0.13	56	3.4	9.2	0.6198	1.6303	0.3020	0.4328
3	720	0.13	88	3.4	5.7	0.6198	1.6303	0.5685	1.3175
4	720	0.13	112	3.4	3.1	0.6198	1.6303	0.7684	3.3170
5	720	0.54	35	1.6	11.5	0.8161	4.4376	0.1272	0.1457
6	720	0.54	56	1.6	9.2	0.8161	4.4376	0.3020	0.4328
7	720	0.54	88	1.6	5.7	0.8161	4.4376	0.5685	1.3175
8	720	0.54	112	1.6	3.1	0.8161	4.4376	0.7684	3.3170
9	720	0.94	35	1.2	11.5	0.8614	6.2141	0.1272	0.1457
10	720	0.94	56	1.2	9.2	0.8614	6.2141	0.3020	0.4328
11	720	0.94	88	1.2	5.7	0.8614	6.2141	0.5685	1.3175
12	720	0.94	112	1.2	3.1	0.8614	6.2141	0.7684	3.3170
13	720	1.2	35	1.1	11.5	0.8776	7.1709	0.1272	0.1457
14	720	1.2	56	1.1	9.2	0.8776	7.1709	0.3020	0.4328
15	720	1.2	88	1.1	5.7	0.8776	7.1709	0.5685	1.3175
16	720	1.2	112	1.1	3.1	0.8776	7.1709	0.7684	3.3170
17	930	0.13	35	5.5	12.4	0.3834	0.6218	0.0636	0.0679
18	930	0.13	56	5.5	10.1	0.3834	0.6218	0.2385	0.3131
19	930	0.13	88	5.5	6.5	0.3834	0.6218	0.5049	1.0199
20	930	0.13	112	5.5	3.9	0.3834	0.6218	0.7048	2.3872
21	930	0.54	35	2.7	12.4	0.7017	2.3528	0.0636	0.0679
22	930	0.54	56	2.7	10.1	0.7017	2.3528	0.2385	0.3131
23	930	0.54	88	2.7	6.5	0.7017	2.3528	0.5049	1.0199
24	930	0.54	112	2.7	3.9	0.7017	2.3528	0.7048	2.3872
25	930	0.94	35	2.0	12.4	0.7752	3.4482	0.0636	0.0679
26	930	0.94	56	2.0	10.1	0.7752	3.4482	0.2385	0.3131
27	930	0.94	88	2.0	6.5	0.7752	3.4482	0.5049	1.0199
28	930	0.94	112	2.0	3.9	0.7752	3.4482	0.7048	2.3872
29	930	1.2	35	1.8	12.4	0.8015	4.0382	0.0636	0.0679
30	930	1.2	56	1.8	10.1	0.8015	4.0382	0.2385	0.3131
31	930	1.2	88	1.8	6.5	0.8015	4.0382	0.5049	1.0199
32	930	1.2	112	1.8	3.9	0.8015	4.0382	0.7048	2.3872
33	1140	0.13	35	9.0	13.2	0.0000	0.0000	0.0000	0.0000
34	1140	0.13	56	9.0	10.9	0.0000	0.0000	0.1749	0.2119
35	1140	0.13	88	9.0	7.4	0.0000	0.0000	0.4413	0.7900
36	1140	0.13	112	9.0	4.7	0.0000	0.0000	0.6412	1.7869
37	1140	0.54	35	4.3	13.2	0.5163	1.0673	0.0000	0.0000
38	1140	0.54	56	4.3	10.9	0.5163	1.0673	0.1749	0.2119
39	1140	0.54	88	4.3	7.4	0.5163	1.0673	0.4413	0.7900
40	1140	0.54	112	4.3	4.7	0.5163	1.0673	0.6412	1.7869
41	1140	0.94	35	3.3	13.2	0.6354	1.7427	0.0000	0.0000
42	1140	0.94	56	3.3	10.9	0.6354	1.7427	0.1749	0.2119
43	1140	0.94	88	3.3	7.4	0.6354	1.7427	0.4413	0.7900
44	1140	0.94	112	3.3	4.7	0.6354	1.7427	0.6412	1.7869
45	1140	1.2	35	2.9	13.2	0.6781	2.1065	0.0000	0.0000
46	1140	1.2	56	2.9	10.9	0.6781	2.1065	0.1749	0.2119
47	1140	1.2	88	2.9	7.4	0.6781	2.1065	0.4413	0.7900
48	1140	1.2	112	2.9	4.7	0.6781	2.1065	0.6412	1.7869

with the highest burnishing force and the lowest burnishing speed. On the basis of initial research it was possible to present the relations defining the influence of the input factors on the output factors in the following criteria functions:

$$S_U = 0.004F - 0.11V_n + 12.05, \tag{6}$$

$$K_{Ra} = \frac{10^{0.001F}}{4.36 \cdot f^{0.51}}, \tag{7}$$

where:
S_U - degree of surface layer relative hardness,
K_{Ra} - surface roughness reduction factor [–],
F - burnishing force [kN],
V_n - burnishing speed [m/min],
f - feed [mm/rev].

Making a search of the adequate range, the optimum process parameters were gained for each criterion function separately. And so, on account of minimum Ra surface roughness factor as well as the maximum S_U surface layer hardness degree, the burnishing process parameters are as follows: $F = 1140$ N, $f = 0.13$ mm/rev and $V_n = 35$ m/min. After applying the obtained variables values to formulas 6 and 7 respectively, the following was reached:

- $K_{Ramax} = 9$ and $S_U = 13.2$ – on account of maximum roughness reduction factor,
- $S_{Umax} = 13.2$ oraz $K_{Ra} = 9$ – on account of maximum hardness degree factor.

The compromise solutions achieved in the research are shown in Tab. 6.

Making use of relations 3 and 4 the deviations of particular objective functions were calculated from their maximum values, and then the best compromise solution was chosen after applying relation 5 (underlined verse in Tab. 6). For this solution, both objective functions have possible identical values, and at the same time are the least distant from the extremes of both functions.

5. Conclusions

Performing the process of burnishing of the X5CrNi1810 stainless steel makes it possible to reduce the mean arithmetic value of R_a roughness profile deviation and to increase S_U surface layer relative hardness degree. The multi criteria optimization conducted by min-max method confirmed the fact that burnishing process should be carried out at the following technological parameters: burnishing force 1.1 kN, burnishing speed 35 m/min, feed 0.13 mm/rev. On the basis of the results obtained it can be stated that these are the optimal parameters with regard to both optimization criteria accepted, at the same time, assuming their identical weights.

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