

A study for determining the most significant parameters of the ball-burnishing process over some roughness parameters of planar surfaces carried out on CNC milling machine

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Abstract. Ball burnishing process often applies for obtaining specifically characteristics in the surface layer of the functional surfaces of the machine parts. Using CNC machines for carrying out this process significantly increases the possibility of control the characteristics of the toolpath of the ball tool and thus to produce regularly distributed roughness with specific size and direction of cells alignment. The current study presents obtained results from L8 Taguchi experimental design for determining the significantly influenced parameters of the ball burnishing process carried out on CNC milling machine on the size and arrangement direction of the cells form regular distributed roughness on planar surfaces.

1 Introduction

For application of the ball burnishing (BB) process, using CNC milling machines to create so-called “regularly distributed roughness” (RDR) on the functional surfaces of the parts it is necessary to create the toolpath of the ball-tool in advance, and then using appropriate CAM software to transform it into corresponding NC-code [1]. To create appropriate toolpaths of the BB tool with optimal length, special curves are used (such as polylines), created by an algorithm described in [1], which is based on system of equations (1).

$$\begin{cases} X_{m,n} = f(D_0, e, d_{fn}, L, i, i_p) \\ Y_{m,n} = f(D_0, e, H, i, i_p) \end{cases} \quad (1)$$

The equations (1) calculates the values of the coordinates $X_{m,n}$ and $Y_{m,n}$ of each point from sinewave curves m_i (see Figure 1 a, c). Then, using certain logical conditions, the algorithm connects these curves into a single coherent polyline, limited to the rectangular flat section with length L , mm and width H , mm, as shown in Figure1, a÷d. The components participating in the system of equations (1) are as follows:

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- $2.e$, mm is the amplitude of the sine waves with wavelength l_{sin} , mm, which follow the path of circles with diameter D_0 , mm;
- d_{fn} , mm is the linear distance between adjacent circular paths;
- n is the index of the current point from sine wave curve ($n=0, 1, 2, \dots, p$), and p is the total number of points contained in the polyline;
- m is the index of the current circular path with diameter D_0 ($m=0, 1, 2, \dots, q$), and q is the number of the needed circular paths (calculated as $q = L/d_{fn}$);
- i , is the number of sine waves with wavelength - l_{sin} , mm, which falling within length of one full circular path (with diameter D_0). It can be calculated as $i = (\pi \cdot D_0)/l_{sin}$;
- i_p is only fractional part of the parameter i , that determines the phase shift between sine waves from the adjacent circular paths with diameter D_0 . The parameter i_p can be changed within a range from 0 to 0.5, but usually its value is set as $i_p \approx 0.15$ [1].

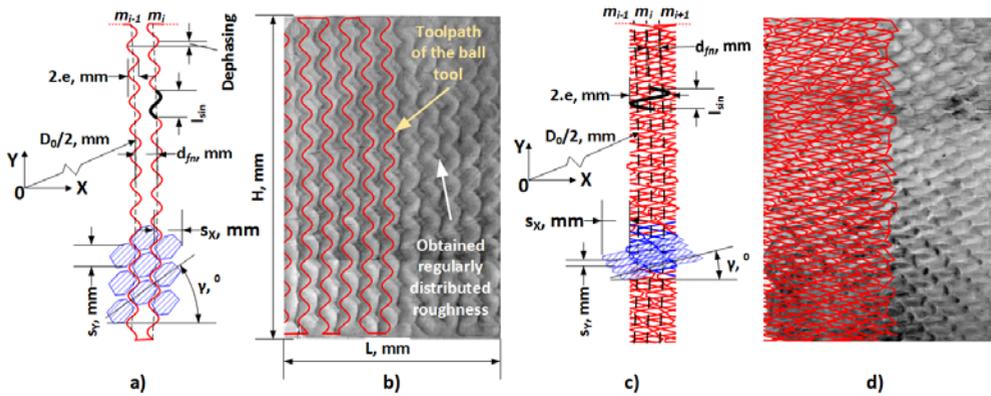


Fig. 1. Example of two types of polylines: defining toolpaths of the ball tool (a, c) and the resulting patterns with RDR (b, d) processed on planar surfaces by using BB process.

By setting certain values of the participating parameters in equations (1), different types of polylines (see Figure 1 a, c) can be obtained, i.e. different types of toolpaths of the ball tool. This will lead to producing different RDR patterns (see Figure 1 b, d) over the processed planar surface. Depending on the pre-set values of amplitude of the sine waves $2.e$, the linear distance between adjacent circular paths d_{fn} , the number of sine waves i , the diameter d_b , mm of the used ball tool, the magnitude of applied compressive force F , N, and physical and mechanical characteristics of the burnished material, the size and shape of the cells may vary significantly. For example, when $2.e < d_{fn}$, (see Figure 1, b) the adjacent sine wave curves have some distance between themselves and in this case it is likely to form a partially regular roughness patterns (i.e. Type III microshape, according to [2], with remaining islands with roughness from transition operation). Respectively, when $2.e \geq d_{fn}$, they can touch or intersect one another, as can be seen from Figure 1, c, d. This results in obtaining completely regular roughness (i.e. Type IV microshape [2], without islets from the previous operation). Referring to Figure 1 a, c, it is easy to see that the parameters e and d_{fn} will have a significant impact on the s_x , mm dimension of resultant cells, while the parameter i (i.e. the number of sine waves, within length of one full circular path) will determine their s_y , mm dimension along the Y-axis. The fractional part of the parameter i_p , determines the phase shift between sine waves from the adjacent circular paths, and will affect the angle γ between the direction of alignment of the cells from RDR and the X-axis, as well as their shape (which can be near to hexagonal or rectangular shape [2, 3]).

Although the polyline representing the tool path generated at the specified values of the elements from (1) can give some preliminary “picture” of how the ball-tool traces will be located, and what cells (by shape and size) will be form on processed surface, but

unfortunately this does not always correspond to the characteristics of the actually obtained RDR. This is because under certain values of the elements of the system of equations (1) (for example when $2.e \gg d_{fn}$), the sinewaves of polyline can intersect themselves in the manner shown in Figure 1, c. Therefore, the visual recognition of the boundaries of the individual RDR cells that will actually be formed on the processed surface can be significantly complicated and even not possible. In addition, in the ball-burnishing process, the movement of the deforming element along to his trajectory causes plastic deformation of the material not only in the vertical direction but also in the horizontal plane of the surface. In a BBP, a plastic deformation rearrangement of the material is made in the contact spot between deforming ball tool and processed surface layer. As a result, the boundaries outlining the cells from RDR are formed. As a certain compressive force is applied to the deforming tool, the degree of deformation (i.e., the resulting depth and width of the trace left by the ball tool) will depend on the magnitude of that force, the diameter of the ball-tool, and physical and mechanical characteristics of the burnished material. However, the system of equations (1) (respectively the algorithm from [1]) does not take into account any of these three substantially affecting on resulting plastic deformation in the surface layer regime parameters of the BB. Hence, the prediction of the resulting shape and plane dimensions (i.e., the size) of the RDR's cells, based only on the geometrical characteristics of the generated polyline-toolpath, would not be correct even when the polyline is of the type, shown in Figure 1, a, b.

Often designing the BB process involves experimental solving of optimization problems requiring the creation of empirical regression models, using some of known DOE approaches. If these optimization experimental studies use all the aforementioned factors, their planning and conducting will be too complicated, and time and resource consuming. Therefore, the main purpose of this work is experimentally determining those parameters, which have most significant influence on the size and arrangement direction of the cells from RDR.

2 Methodology of experimental study

2.1 Selecting experimental plan and factors

As is known the main regime parameters of BB process are burnishing force F , N, diameter of the ball tool d_b , mm, and burnishing feed rate f , mm/min [2, 3]. If they are added to the components in (1) which defines the characteristics of the polyline, seven factors are obtained that may have (in varying degree) impact on the size and deploying the cells from RDR. If the full factorial design were used to determining the degree of impact of these seven factors, it would have $2^7 = 128$ runs, which would greatly complicate this experimental study. Thus, it was decided the L8 (2^7) Taguchi design [4, 5] to be used, because this array requires only eight runs, it is orthogonal, and factor levels are weighted equally across the entire design. L8 design plan is composed of seven factors that have two levels: low and high. In the present experimental study, the identified seven factors and their low and high levels are shown in Table 1. The L8 Taguchi design with combinations of low and high levels of the factors for the eight needed runs is shown in the Table 2.

2.2 Conducting the experiment and processing the experimental data

The used specimen are made of sheet from Al-alloy type 2024-T3 (AlCu4Mg1, ISO 6361-2) with thickness $\delta=10,4$ mm, width 160 mm, and height 80 mm. Eight 30×30 mm square areas are processed by BB on the plate, using 2.5-axis CNC-milling machine, type PB-501.24 "HEBROS" (see Figure 2 a, b) and specially designed tool [6, 7]. Each of these areas

processed with combination of the regime parameters, corresponding to the each run from the experimental design, shown in Table 2.

Table 1. Values of the low and high levels of the experimental factors.

No	Name of the factors	Units	Low level	High level
1	Diameter of the ball tool, d_b	mm	14	22
2	Number of sine waves (including phase shift), $i+i_p$	-	600,15	1200,15
3	Diameter of the base circle, D_0	mm	300	500
4	Burnishing feed rate, f	mm/min	150	300
5	Amplitude of the sine waves, e	mm	0.5	2.5
6	Linear distance between adjacent circular paths, d_{fn}	mm	2.5	5.0
7	Burnishing force, F	N	700	2260

Table 2. L8 Taguchi experimental design and obtained results for cells from RDR.

Run	Values of the low and high levels of the experimental factors							Experimental results		
	d_b , mm	$i+i_p$	D_0 ,mm	f , mm/min	e , mm	d_{fn} , mm	F , N	\overline{S}_X , mm	\overline{S}_Y , mm	$\overline{\gamma}$, °
1	14	600.15	300	150	0.5	2.5	700	1.06	1.40	45.27
2	14	600.15	300	300	2.5	5	2260	2.16	1.73	31.62
3	14	1200.15	500	150	0.5	5	2260	1.94	1.47	27.33
4	14	1200.15	500	300	2.5	2.5	700	1.87	1.03	27.59
5	22	600.15	500	150	2.5	2.5	2260	1.88	1.05	33.30
6	22	600.15	500	300	0.5	5	700	2.22	2.97	30.52
7	22	1200.15	300	150	2.5	5	700	2.91	1.07	13.50
8	22	1200.15	300	300	0.5	2.5	2260	1.04	0.73	30.34

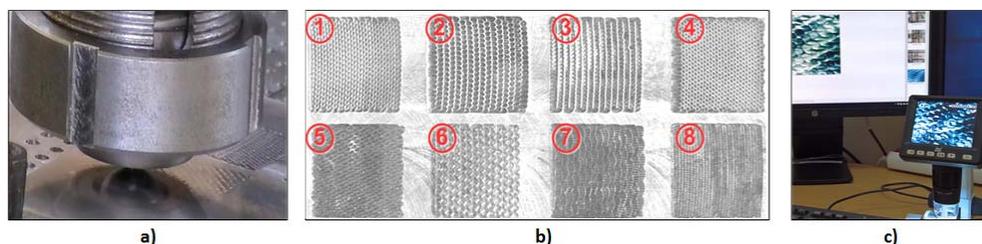


Fig. 2. a) Processing RDR by BB using CNC-milling machine; b) The experimental specimen with eight burnished areas, according to L8 design; c) Microscopic measuring of the dimensions S_X , S_Y , and γ of the cells from the RDR.

To determine the main effects of the regime parameters of the BB process over the size and arrangement direction of the cells from RDR, two steps S_X and S_Y (respectively along the axes X and Y) are used, and an angle γ , which defines the direction of cell alignment relative to the X-axis (see Figure 1, a, c). To determine these three parameters a USB microscope DNT 12 MPix and DigiMicro Lab5.0 software were used. Measurements are done under magnification up to $50\times$, and with an accuracy of 0.01 mm. For each run of the Table 2, the parameters S_X , S_Y and γ were measured five times for random cells from the RDR for all eight runs. The obtained sample mean values \overline{S}_X , \overline{S}_Y , $\overline{\gamma}$ are shown in section “Experimental results” of the Table 2. The t-statistic technique [5, 7] was used to check the sample means \overline{S}_X , \overline{S}_Y , $\overline{\gamma}$, and it was found that they fall within the confidence intervals (at 95% confidence level).

The measured values are entered and average response for each combination of control factor levels are calculated, using statistical software Minitab [5]. As a result, three plots of the main effects are built (see Figure 3 a, c, e). For sorting the regime parameters (i.e. factors) according to their levels of significance, Pareto analysis technique is used, based on calculated magnitudes of their half effects (see Figure 3.b, d, e).

3 Results and discussion

The obtained effects graphs and Pareto histograms (see Figure 3 a-f) shows the distributions of the BB's regime parameters. They arranged in descending order by the degree of their influence on the steps S_X and S_Y , and the angle γ of the cells arrangement direction.

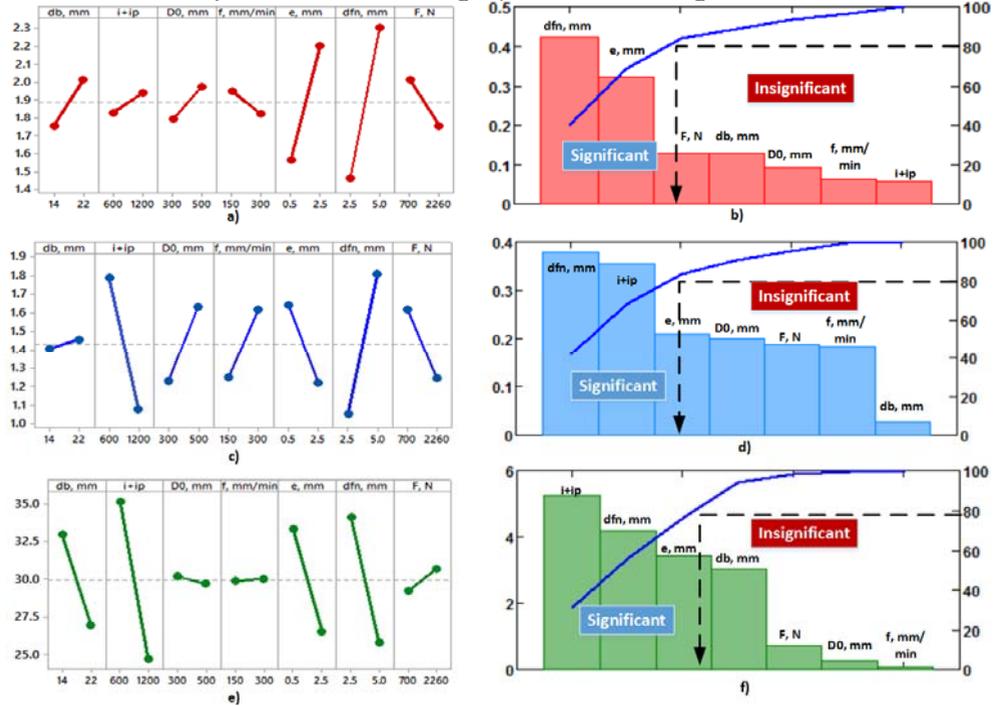


Fig. 3. Effect graphs, the half effects histograms and the cumulative percentages in Pareto plots for: a), b) step S_X , c), d) step S_Y , and e), f) angle γ of arrangement direction of the cells from RDR.

Using cumulative Pareto percentages curves (see Figure 3 b, d, f), and applying the Pareto principle (also known as the 80/20 rule), the following dependencies are highlighted:

- On the size of the step S_X approximately 80% of the influence is given by the parameters d_{fn} and e (see Figure 1 a, c), and the maximum value of S_X occurs when both of these two parameters have high levels;
- On the size of the step S_Y approximately 80% of the influence is given by the parameters d_{fn} and $i+i_p$ (see Figure 1 a, c), and the maximum value of S_Y occurs when d_{fn} has high level and $i+i_p$ has low level;
- On the magnitude of the angle γ approximately 80% of the influence is given by the parameters $i+i_p$, d_{fn} and e (see Figure 1 a, c), and the maximum value of γ occurs when all three parameters have low levels;

Referring to the graphs from Figure 1 a, c, it can be seen that the obtained results from the conducted experimental study largely confirm the logically expected influence of these parameters (d_{fn} , e and $i+i_p$) in the formation of the polyline's characteristics. Consequently, it can be considered that these three parameters will have highest impact on the toolpath's characteristics of the ball tool within the area processed by BB.

Seems like the parameter D_0 (diameter of the base circle) has no significant effect on the size of the RDR's cells and the direction of their alignment. This is most likely due to its small curvature resulting from the large difference between low level of the diameter D_0 (see Table 1) and the width of the burnished section $H=30$ mm. In order to minimize its impact at larger widths of the burnished areas H , the D_0 values should also be increased.

The remaining BB regime parameters (burnishing force F , burnishing feed rate f , and diameter of the ball tool, d_b) also have a negligible effect on formation of the size and arrangement direction of the cells from RDR.

4 Conclusions

Based on conducted experimental study and the obtained results could be made following main conclusions:

- The parameters $i+i_p$, d_{fi} and e , participating in the system of equations (1), and which determines largely characteristics of the obtained polylines (see Figure 1.a, c) have the most great influence on the steps S_x , S_y , and the angle γ of the cells arrangement direction. If the application of the BB process is related to achieving RDR's cells with specified size and direction of alignment, they can be used to adjust polyline's (respective toolpath of the ball tool) properties and achieve these requirements.

- The main regime parameters of the BB process: burnishing force F , burnishing feed rate f , and diameter of the ball tool, d_b have small effects in the formation of the size and arrangement of the RDR's cells within processed planar surface;

- The diameter of the base circle D_0 around which the sinusoidal curves of the polyline are obtained, has no significant effect on the size and alignment of the RDR's cells, when the condition $D_0 \gg H$ is met (see Figure 1, a). When CNC-machines is used for BB processing, the diameter D_0 has rather virtual meaning, as an parameter participating in (1) and can be changed widely without hardware constraints, as opposed to manually controlled machines where it is usually a structural element of the special developed additional vibratory burnishing devices, and cannot be changed easily within wide limits;

- Because the required ball-tool trajectories are calculated mathematically and then execute programmatically by the CNC-machine, this results in greater uniformity of the shape, dimensions and arrangement direction of the cells from RDR.

Our future work will be focused on investigation on the influence of the involved in system of equations (1) parameters on the dimensions and arrangement direction of the cells from RDR, when processing none planar surfaces by BB process.

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