ANALYSIS OF THE EFFECT OF MACHINING PARAMETERS ON THE SURFACE ROUGHNESS IN BORE HONING

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Abstract:

Honing is a wide-spread applied machining procedure in finish manufacturing of high precision bores (for example surfaces in internal combustion engines). Machining procedures can be analysed from the point of view of the energy efficiency, productivity, surface quality, etc. In this paper the achievable surface quality after the honing process is studied on sleeves with EN-GJL-250 lamellar cast iron alloy material. The cutting experiments were planned according to the 2^3 full factorial design of experiments method. Two levels of the analysed factors were chosen in this study. The pressure on the honing stone, the feed of the tool and the average grain size are changed, which resulted in 8 experimental setups. After the roughness measurement and profile evaluation, the main effects are analysed of these 3 parameters. Equations were determined according to the principle of the design of experiment method. The effect of the studied machining parameters is analysed by the application of these equations. The findings in this paper make it possible to explain some phenomenon in the honing process and allow the planning of future experiments in this topic. It was found that lower pressure, higher feed, and finer grains are favourable to achieve low roughness values.

1 Introduction

The different finishing procedures have many attributes which can be and must be studied in order to circumscribe the application range of a given machining process. Researchers must analyse among others the productivity, energy efficiency, machined surface quality, shape, and size accuracy. In the past many kinds of machining procedures are developed, where the finishing procedures have a greater attention nowadays due to the fact, that the properties of the produced parts depend on these. An important area in manufacturing is the production of bores with good quality which are used in the internal combustion engine manufacturing for example. There is ongoing research to improve the functionality of machined surfaces by different methods, such as the use of special environmentally friendly additives in the lubricant between the contacting surfaces [1]; or the application of bio lubricants which improved the lubricating potentials by reducing the Coefficient of friction and wear rate [2]. However, the functional properties are still depending on the applied finishing procedure. For example, the wear of the components is greatly affected by the surface roughness [3] and the applied lubrication [4]. The main machining procedure to finish these parts are honing, which needs to be adjusted for the current challenges. Thus, in this paper, the machined surface quality of honed bores is studied.

The optimization of the surface quality surface is a complex task, where the optimal values of the process parameters need to be found. These have various effect on the machined surface, like the alteration of the stress state belove the surface. In abrasive machining a factor, which affects the stresses and localization area is the grain concentration [5]. However, Yang et al. also showed, that if the grain size increased, the surface roughness greatly changed [6]. In their work, this had the most effect, while the radial and axial speed had little effect on the surface roughness. Szabó also showed, that the material removal rate can be easily modified

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by the change of grain sizes [7]. Sabri et al. also proved, that the end surface quality and topography of the machined parts can be advantageously modified by the proper change of the grain size [8]. Kundrák et al. also proved in abrasive machining, that a higher elastic modulus of the bond can increase the strength of grain retention, which provides an increase in grinding performance and a reduction in the specific consumption of grains [9]. It is also important to help the self-sharpening of the abrasive tools by revealing new grains on the working surface [10]. Sender and Buj-Corral showed by the analyses of honing process, that the stroke length, followed by the pressure, greatly influences shape deviation [11]. Goelden et al. done a simulation and experimental study, where they proved that the prescribed roughness can be achieved by the increase of pressure and the decrease of stroke number [12]. In conclusion, in this study the effect of the grain size, pressure and feed is analysed in bore honing. There are many roughness parameters, which can be used according to the functional requirements of the surfaces.

The importance of choosing the proper roughness parameter cannot be highlighted enough [13]. There can be also problem with the roughness changes locally in surfaces with untraditional geometries, as shown by Matras et al. in their study of curvilinear surfaces [14]. That is also important to optimise these values by the application of mathematical analysis [15], Artificial Neural Network method [16] and other methods. In this study a design of experiment method is applied, which is commonly used in the practice [17]. Tamang et al. also applied an experimental design method to optimise the analysed parameters individually, from which one was the Arithmetic Mean Height of the roughness profile [18]. Buj-Corral et al. applied 2^{5-1} factorial design in their study to analyse the honing process and they found that the main factor affecting roughness was grain size in both cases, followed by pressure [19]. This experimental method is used to determine the main effect of the analysed parameters and it gives us a prediction about the expected outcomes not only in the points defined in the setup parameters but between them as well. This assumption can be used to decide the direction of future research in the topic.

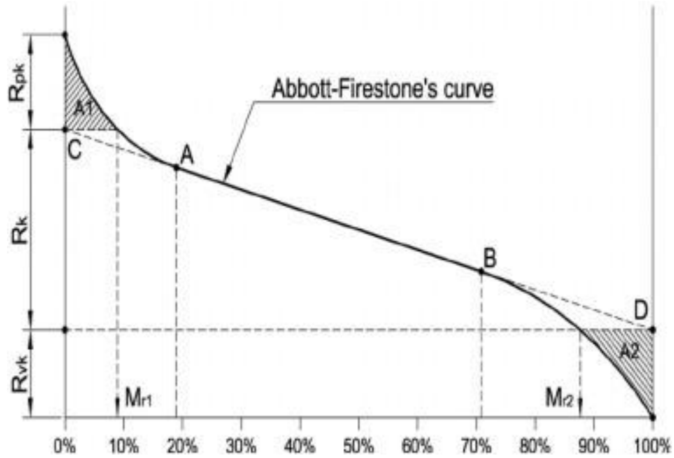

Figure 1. The studied Abbott-firestone curve [20].

Among the most applied roughness parameters, the functional properties of the surface can be described well with the Abbot-Firestone curve [20]. Main parameters of the curve are explained based on Figure 1. Here the peak-to-valley distance is divided into 3 sub parameters. The Core Roughness (R_k) is the measure of the main material volume, which will bear the load during the working conditions. The Reduced Peak Height (R_{pk}) describes that part of the surface profile, which will be worn out first during the initial contact of the interacting parts. The Reduced Valley Depth (R_{vk}) shows that part of the profile, where the oil (or in a worse case debris) is stored.

The material ratios (M_{r1} and M_{r2}) and area parameters (A_1 and A_2) can also be seen in Figure 1, however the analysis of these parameters are not the topic of this current study. In this paper the Maximum Height of the Profile (R_z) are also analysed among the Core Roughness, Reduced Peak Height, Reduced Valley Depth, as it is a commonly used roughness parameter.

2 Experimental method and setup

The aim of the experiments was to study the effect of several parameters (pressure, feed, grain size) on the surface roughness in bore honing. The values of the analysed parameters were chosen according to the rules of 2^3 full factorial design of experiments. The machining was done with the different setups on a WMW 270/700 honing machine, which was provided by Belcord Kft. in Eger, Hungary (their help is greatly appreciated). The honing experiments were carried out on sleeves with 192 mm bore length and 88 mm inner diameter. EN-GJL-250 lamellar cast iron alloy material was machined, which have at least 250 MPa Tensile Strength, 210 HB Hardness, 110 kN/mm^2 Elasticity modulus, 950 MPa Compressive Strength.

The applied honing tool six slot 60° from each other where the honing stones are clamped during the machining. The honing stones were 120 mm length bars with a 10 mm x 10 mm square cross-section. Two kinds of abrasive material were used, which had Al_2O_3 grains in a synthetic resin binder with a dense structure. One tool had coarse grains with size code: 80 and average grain size (d_k): 190 µm; while the other tool had finer grains with size code 240 and average grain size (d_k): 45 µm. Among the cutting parameters, the cutting speed (v_c) was fixed to 200 m/min. The applied pressure on the honing stone (p) was adjusted to 7 bar and 13 bar, the feed per revolutions (v_f, which resulted from the axial movement of the cutting tool during one rotation) was set to 25 mm/rev and 75 mm/rev. The resulted setups, the set parameters and the design matrix for the factorial design can be seen in Table 1.

Table 1. The adjusted parameters and design matrix for the 8 experimental setups.

Setup	Selected factors			Design matrix		
	p [bar]	v_f [mm/rev]	d_k [µm]	p' [-]	v_f' [-]	d_k' [-]
1	7	25	45	-1	-1	-1
2	13	25	45	1	-1	-1
3	7	75	45	-1	1	-1
4	13	75	45	1	1	-1
5	7	25	190	-1	-1	1
6	13	25	190	1	-1	1
7	7	75	190	-1	1	1
8	13	75	190	1	1	1

Measurements were carried out on the workpieces after the cutting experiments with a Mitutoyo SJ-301 Surftest roughness measurement device. The roughness profiles were registered on three generatrix of each bore. The measured profiles were evaluated with the AltiMap Premium 6 surface analysis software.

The analysed parameters of the two-dimensional (2D, linear) profile were (ISO 21920:2021):

- R_z – Maximum Height of the roughness profile [µm]
- R_k – Core Roughness, is a measure of the core (peak to valley) roughness of the profile [µm]
- R_{pk} – Reduced Peak Height, is a measure of the peak height above the core roughness [µm]
- R_{vk} – Reduced Valley Depth, is a measure of the valley depth below the core roughness [µm]

Equations were determined for the study based on the measurement results, which were worked out using the form in Equation (1) according to the 2^3 factorial design method. The dependent value is y and k_i (i = 1, 2, 3, 12, 13, 23, 123) are the coefficients describing the effect of the different factors on the dependent value. The independent variables are the pressure (p), feed (v_f) and average grain size (d_k).

$$y(p, v_f, d_k) = k_0 + k_1 p + k_2 v_f + k_3 d_k + k_{12} p v_f + k_{13} p d_k + k_{23} v_f d_k + k_{123} p v_f d_k \quad (1)$$

Table 2. Measured values of R_z, R_k, R_{pk} and R_{vk} and their average.

		Setup							
		1	2	3	4	5	6	7	8
R_z [μm]	1	2.20	2.93	7.67	1.79	5.26	6.75	7.89	4.65
	2	2.03	3.87	3.49	1.83	5.10	6.17	3.14	4.91
	3	2.16	3.38	1.18	1.89	4.70	6.26	1.39	4.55
	Avg.	2.13	3.39	4.11	1.84	5.02	6.39	4.14	4.70
R_k [μm]	1	0.87	1.12	0.52	0.70	2.33	3.51	1.40	3.21
	2	0.08	1.34	0.64	0.67	2.24	3.09	1.41	4.12
	3	0.97	1.24	0.51	0.76	1.86	3.06	1.63	3.49
	Avg.	0.64	1.24	0.56	0.71	2.14	3.22	1.48	3.61
R_{pk} [μm]	1	0.25	0.37	0.21	0.32	0.78	1.05	0.42	0.96
	2	0.27	0.49	0.23	0.22	0.48	0.85	0.42	0.63
	3	0.36	0.34	0.21	0.24	0.89	0.92	0.57	0.77
	Avg.	0.29	0.40	0.22	0.26	0.72	0.94	0.47	0.79
R_{vk} [μm]	1	0.67	0.98	0.23	0.52	1.49	1.70	0.77	1.16
	2	0.62	1.57	0.29	0.56	2.05	1.68	0.77	1.75
	3	0.52	1.38	0.26	0.59	1.16	1.78	0.89	1.10
	Avg.	0.60	1.31	0.26	0.56	1.57	1.72	0.81	1.33

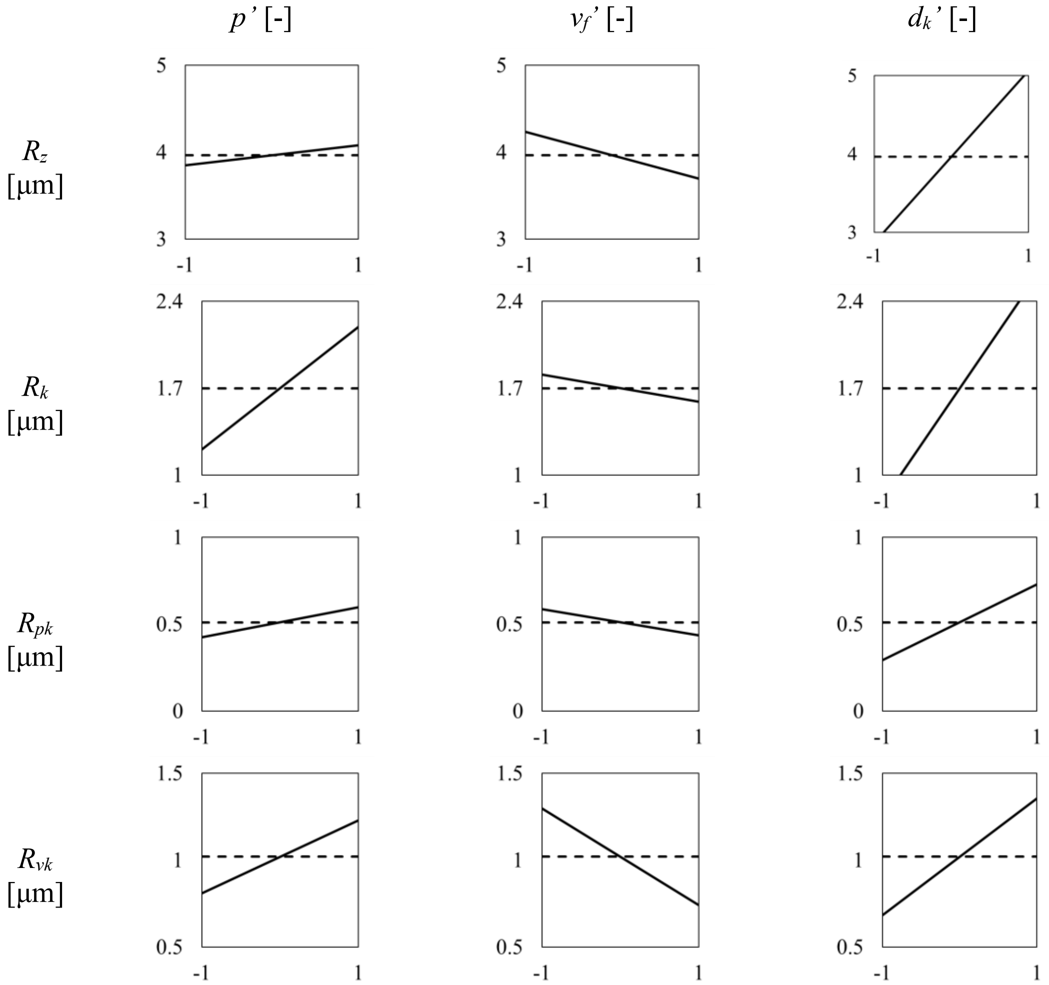

Figure 2. Main effect plot of p, v_f, d_k.

3 Results and discussion

After the cutting experiments, three measurements were carried out on 3 different generatrix on each machined workpiece. A value of R_z, R_k, R_{pk} and R_{vk} are evaluated from the registered profiles, which were averaged for each setup. The results of the measurements and the calculated averages can be seen in Table 2. Main effect plots were drawn for the initial evaluation of the effect of the three studied parameter. Each analysed roughness parameters are studied separately according to the following. First the mean value of the averaged values is calculated, which are represented by a dashed line. Then two mean values were calculated again for the three studied cutting parameters, where the results are separated according to the lower (-1) and upper (1) limit of p, v_f and d_k. These two averages are connected with a continuous line. The direction and gradient of the slope of these lines describe the main effect of the cutting parameter on the studied roughness parameters. The resulted main effect plots of the different cutting parameters on the studied roughness parameters can be seen in Figure 2. From these figures, the following conclusions can be drawn.

The increase of pressure acting on the honing stone has an increasing effect on the Core Roughness and the Reduced Valley Depth, while it has almost no effect on the Maximum Height of the roughness profile and the Reduced Peak Height. The increase of the feed typically decreases the studied roughness values with the greatest effect on the Reduced Valley Depth. Greater grain sizes results in increasing values for every parameter. The grain size has the most effect on the R_z parameter, followed by the feed and pressure. The pressure and the grain size has almost the same effect on the R_k parameter, while the alteration of feed has almost no effect. The R_{pk} parameter is almost unaffected by the change of the pressure and feed, while the increase of the grain size has an increasing effect on it. Finally, the R_{vk} parameter increases by the increase of p and d_k, while it decreases by the increase of v_f. The study of the main effects is followed by the detailed analysis of the measurement results, where further parameters are introduced. The R_k, R_{vk}, and R_{pk} values can be explained more throughout, if their ratio is also taken into consideration. A given value of the Reduced Peak Height or Reduced Vally Depth has a different meaning if the Core Roughness is different. Therefore, the ratio of the Reduced Peak Height to the Core Roughness ($R_{p/k}$) and the ratio of the Reduced Valley Depth to the Core Roughness ($R_{v/k}$) are also calculated. These parameters are called "ratio parameters", which can be determined as seen in Equation 2, and the calculated values can be seen in Table 3.

$$R_{p/k} = R_{pk} / R_k \qquad R_{v/k} = R_{vk} / R_k \tag{2}$$

Table 3. Calculation of the ratio parameters.

		Setup							
		1	2	3	4	5	6	7	8
R_k	[μm]	0.64	1.24	0.56	0.71	2.14	3.22	1.48	3.61
R_{pk}	[μm]	0.29	0.40	0.22	0.26	0.72	0.94	0.47	0.79
$R_{p/k}$	[-]	0.45	0.32	0.39	0.37	0.34	0.29	0.32	0.22
R_{vk}	[μm]	0.60	1.31	0.26	0.56	1.57	1.72	0.81	1.33
$R_{v/k}$	[-]	0.94	1.06	0.46	0.79	0.73	0.53	0.55	0.37

In the research methods it is stated that equations will be constructed according to the 2^3-Factorial Design in the form of Equation 1. The measured results were evaluated as described above. The equations are determined for the analysed roughness parameters, which can be seen in the following order: Maximum Height of the Profile in Eq. 3, Core Roughness in Eq. 4, Reduced Peak Height in Eq. 5, Reduced Valley Depth in Eq. 6, ratio of the Reduced Peak Height to the reduced Valley Depth in Eq. 7, and ratio of the Reduced Vally Depth to the reduced Valley Depth in Eq. 8. These equations give a precise result of each analysed roughness parameter, however if a given process parameter is adjusted to a value which was not presented in the setup parameters, there could be an error.

The nearer the newly adjusted parameter to the determined setup parameters, the lesser will be the calculation error. Further research will be carried out according to the result of this study, which will be applied to determine the following experimental setup parameters.

Equations 3-8 presents the calculatable formulas for each analysed roughness value; however, it is difficult to discuss the results from these. Figures were drawn based on these equations for the better understanding of the process.

$$R_z(p, v_f, d_k) = -4.182 + 0.568p + 0.159v_f + 0.039d_k - 0.0146pv_f - \\ - 0.0014pd_k - 0.000832v_fd_k + 0.0000625pv_fd_k \quad (2)$$

$$R_k(p, v_f, d_k) = -0.935 + 0.151p + 0.023v_f + 0.01452d_k - 0.0031pv_f - \\ - 0.0003pd_k - 0.000321v_fd_k + 0.0000345pv_fd_k \quad (3)$$

$$R_{pk}(p, v_f, d_k) = 0.0035 + 0.0228p + 0.0025v_f + 0.00338d_k - 0.00041pv_f + \\ + 0.0000287pd_k - 0.00005218v_fd_k + 0.00000391pv_fd_k \quad (4)$$

$$R_{vk}(p, v_f, d_k) = -1.008 + 0.2016p + 0.01102v_f + 0.01578d_k - 0.002174pv_f - \\ - 0.001092pd_k - 0.0001834v_fd_k + 0.00001793pv_fd_k \quad (5)$$

$$R_{p/k}(p, v_f, d_k) = 0.798 - 0.03895p - 0.005031v_f - 0.002276d_k + 0.0005098pv_f + \\ + 0.0001897pd_k + 0.00003115v_fd_k - 0.00000363pv_fd_k \quad (6)$$

$$R_{v/k}(p, v_f, d_k) = 1.181 + 0.01439p - 0.01738v_f - 0.0005768d_k + 0.0008762pv_f - \\ - 0.0002598pd_k + 0.00006932v_fd_k - 0.00000425pv_fd_k \quad (7)$$

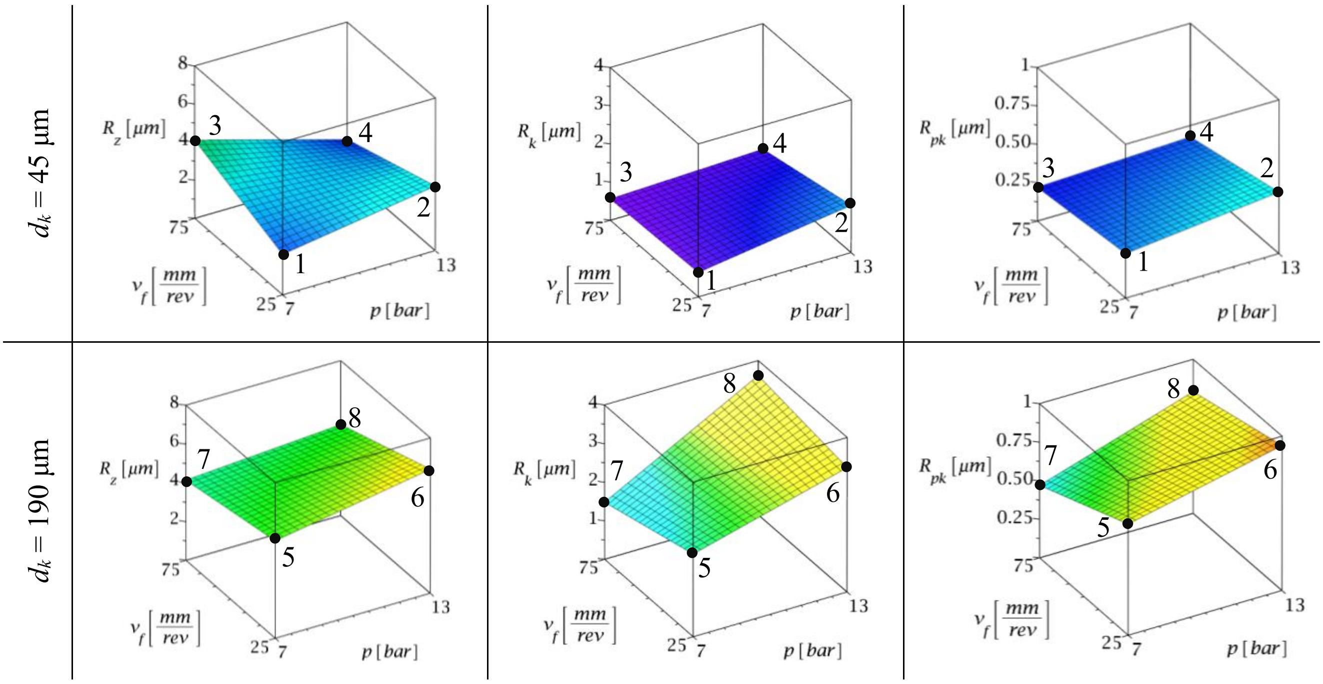

Figure 3. 3D diagrams of the R_z, R_k and R_{pk} parameters on different grain sizes.

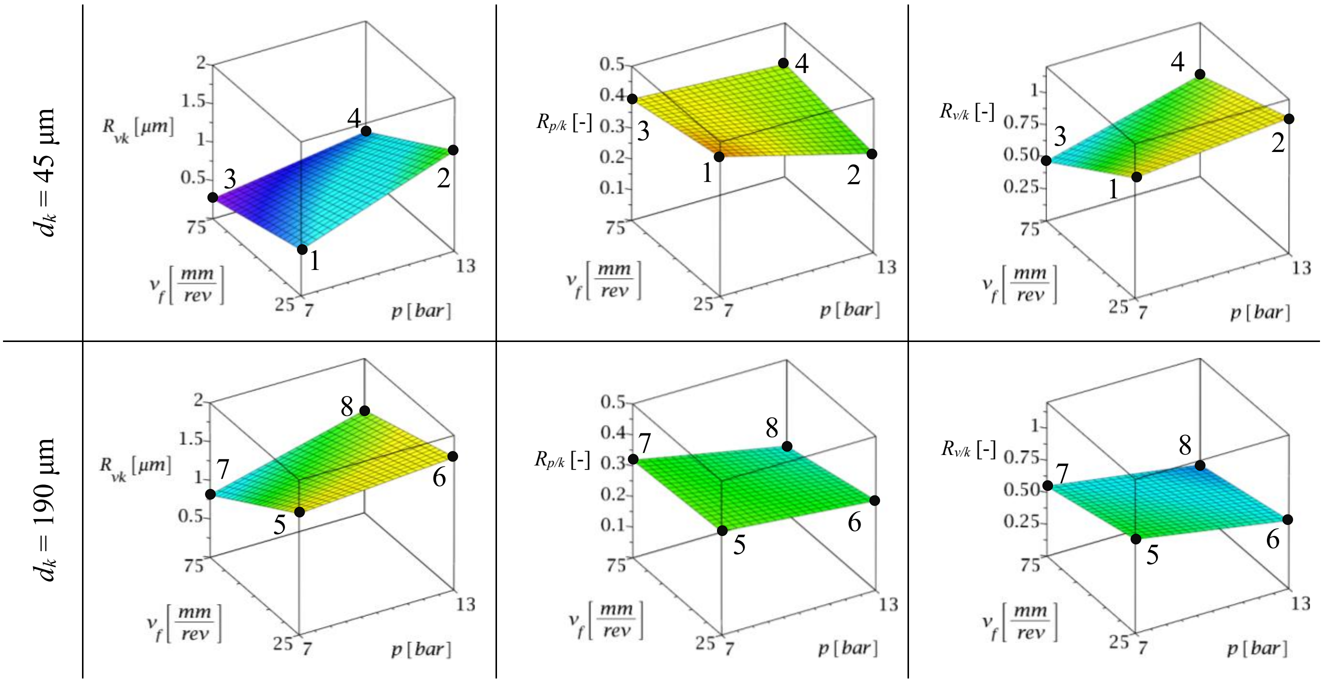

Figure 4. 3D diagrams of the R_{vk}, $R_{p/k}$ and $R_{v/k}$ parameters on different grain sizes.

Two 3D diagrams were created for each roughness value on the two levels of the grain size. This is done due to the fact, that the grain size cannot be adjusted continuously, the cutting tool needs to be disassembled to change the honing tool to a different coarseness. Therefore, the two horizontal axles of these 3D graphs represent the pressure and the feed, while the vertical axle represent the analysed roughness value. Figure 3 shows the alteration effect of the analysed cutting parameters on the Maximum Height of the Profile, Core Roughness and Reduced Peak Heigh. Figure 4 presents the effect of the cutting parameters on the Reduced Vally Depth and the ratio parameters. The first conclusion, which can be drawn from Figure 3 and 4, is the increasing effect of the grain size increase. By the application of coarser honing stone (changing the average grain size from 45 µm to 190 µm) an average two-fold increase in the R_z; an average 3.4-fold increase in the R_k; an average 2.5-fold increase in the R_{pk}; and a 2.3-fold increase in the R_{vk} can be observed. However, the increase of the grain size decreases the ratio parameters sightly (about 70% to their original value on average). The grain in the honing stone produces the micro-scratches on the machined surface, and the material removal is done by the repetition of those.

The size of the grains modifies the shape and depth of these scratches, where a coarser tool material results in a deeper and wider valley. This phenomenon causes the increase in the analysed roughness parameters. Therefore, it can be concluded, that the resulted surface roughness can be manipulated very easily by the application of bigger or smaller grains. However, decrease of the ratio parameters means different functional attributes of the surfaces, which must be further analysed in a following study. The left-third part of Figure 3 shows the alteration of the Maximum Height of Profile. Increasing the pressure on the lower feed value results in a 1.4-fold increase in *Rz*, while its value decreases to its half when the higher feed is applied. Increasing the feed decreases R_z to 0.8-fold in most cases, while when lower pressure and smaller grain is applied, R_z shows a 2-fold increase with the increase of the feed. The Middle part of Figure 3 presents the change of Core Roughness. The increase of the pressure leads to a 1.8-fold increase in this value on average, while the increase of the feed leads to an 0.7-fold decrease of average. The last part of Figure 3 shows the alteration of the Reduced Peak Height. A 1.4-fold increase can be observed by the increase of the pressure; however, a 1.4-fold decrease can be seen if the feed increased.

The left-third part of Figure 4 shows the change of the Reduced Valley Depth. Here a similar directional change can be seen as the previous roughness parameter, but here the extent is higher. The increase of the pressure leads to a 1.7-fold increase in the R_{vk}, while the increase of the feed results in a 1.8-fold decrease. The ratio parameters also analysed. The increase of pressure leads to a 1.2-fold decrease, while the increase of feeds has almost no effect on the Reduced Peak Height to Core roughness ratio. The other ratio parameter behaves the opposite way. The increase of the pressure leads almost no change, while the increase of the feed leads to a 1.5-fold decrease in the reduced Valley Depth to Core roughness ratio. The increase of pressure causes the grains to make a deeper scratch on the surface, while the increase of feed leads to higher repetition length of these scratches. This phenomenon explains the above-described change in the roughness values.

4 Conclusions

The machined surface roughness is a frequently analysed attribute of different machining procedures because this is a representation of the quality and functionality of the produced part. In this paper, the Maximum Height of Profile, the Core roughness, the Reduced Peak Height, the Reduced Valley Depth, and the ratios of the previous three were studied in bore honing. Experiments were carried out according to the full factorial experimental design plan with three factors: pressure, feed, and average grain size. Based on the results of this paper, a new experimental plan will be worked out to further analyse the effect of these parameters. By the application of Full Factorial Design of Experiments method, the to be analysed parameter range for the studied technological parameters can be chosen properly and cost-effectively.

The most important findings are the following:

- Lower pressure, higher feed and finer grains are favourable to achieve low roughness values.
- The grain size has the most significant effect from the analysed cutting parameters.
- The increase of the pressure resulted in a 1.1-1.8-fold increase in the roughness parameters.
- The increase of the feed rate had no effect on the R_z and R_k values, while it increases the Reduced Peak Height and Reduced Valley Depth parameters.

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