GU J Sci 30(1): 111-119 (2017)

Gazi University

Journal of Science

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Optimization of Honing Parameters for Renewal of Cylinder Liners

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Article Info

Received: 20/10/2016
Accepted: 12/01/2017

Keywords

Honing
Surface roughness
Optimization
Taguchi method

Abstract

This study presented the optimization of honing parameters for surface roughness in plateau honing process used for renewal of engine cylinders. The honing experiments were performed based on Taguchi L_9 orthogonal array. The honing parameters directly affected on surface roughness (*Ra*) were determined as linear speed (m/min), grain size and number of stroke with three different levels. These levels were adjusted by considering honing industry and investigations on honing process. The results of variance analysis showed that the most important factor on surface roughness is the grain size while number of stroke has insignificant effect. Finally, an optimization study has been performed with "the smaller the better" method and then confirmation experiment has been conducted. The results have shown that the optimum conditions for better surface roughness were determined as feed rate of 10 m/min, grain size of 220 and stroke number of 6 according to analysis of signal-to-noise (*S/N*) ratios under these cutting conditions. According to confirmation experiment, the difference between experiment and the calculated value was determined as 2.5%. Thus, the optimum levels of honing parameters for *Ra* were confirmed as confident in renewal of engine cylinders.

1. INTRODUCTION

Honing is a machining process using honing stones consisting of abrasive grains given a form of very fine powder. Its cutting speed is very low compared to grinding. This operation is used to remove the waviness and traces of grinding or cutting tool occurred in drilling process and also used for finish hole size with desired surface quality. Honing is both applied with the special apparatus or honing machines and by hand. Honing processes are used in machining of valves, gears bearing rings and the other bed bearings, especially in the engine cylinder liners.

Recently, there are conducted numerous statistical and experimental researches based on design and analysis of experimental methods for determining the influences of cutting parameters on surface roughness in plateau honing of cylinder liners. Ertuğrul and Çınar [1] experimentally investigated on the effects of some design and operating parameters on oil consumption and engine performance in a diesel engine with four-stroke. In this experimental study, the effects of cylinder surface roughness, honing angle and oil ring on oil consumption and engine performance were chosen as honing characteristics. The authors indicated that the rate of oil consumption to fuel consumption is higher according to industrial standards due to deep traces on cylindrical surfaces. Moreover, it was found that the honing angle of 45 obtained with honing process by honing stones with fine grain size decrease the oil consumption. Cabanettes et al. [2] offers to plot the roughness deviations by using confocal-3D measuring equipment for examining any region of cylinder liners. The result shows that only areal reduced summit height, arithmetic mean summit curvature and core roughness depth make correlation with the honing tool wear specific to each cylinder. Tailor made parameters such as honing angle, plateau coverage and groove coverage specify similar results. Actually, as the honing tool wears down, the cylinder liner surfaces get rougher plateau or peak and sharpness showing that ploughing occurs instead of cutting. Corral et al. [3] investigated on effects of different parameters in rough honing on surface roughness and material removal rate with CBN abrasives. The authors showed that the most influential factors are grain size, pressure and density of abrasive on roughness while grain size and pressure, followed by tangential speed on material removal rate. The optimum Ra is obtained at lowest grain size, pressure values and the highest density, tangential speed and linear speed values. Troglio [4] studied the effects of abrasive grain size, lubricating oil and workpiece material on

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roughness *Ra* or *Rk* parameters. In addition, the author investigated the influence of honing parameters on roundness and cylindricity. Also, it was determined tool wear, consumed power, material removal rate and specific energy after a honing process for three different materials. Corral and Calvet [5] used steel cylinders for honing process with CBN tools for determining the change of roughness. The results showed that cylinders roughness increased mainly with abrasive grain size, followed by honing head pressure while tangential speed affected roughness slightly. Bai and Zhang [6] researched the variability of pressure, speed and cross-hatch angle to increase efficiency of the honing process performed with honing stone by grain size 220. It was acquired highest material removal rate at a cross-hatch angle between 40° and 60°. Honing pressure is one of the most significant parameters on roughness. As a different study of Corral et al. [7], it was presented a new methodology for material removal rate in plateau honing to St-52 steel cylinders. Cylinder surfaces were machined by plateau honing under different conditions such as grain size and number of strokes in order to determine the accuracy of probability parameters. The results showed that the difference in area of Abbott–Firestone curve between for the rough honing and the finish honing is proportional to the material removal rate in the finishing operation. Sivatte et al. [8] performed an indirect model for roughness in rough honing processes of St-52 steel cylinders with different honing parameters as a function of required Ra. It was indicated that the surface roughness increase with increasing grain size and density according to experimental results based on Taguchi method. The indirect model showed about 85% confirmation to experimental results and so author concluded the model is considered to be validated. Silva et al. [9] applied a particle swarm optimization to achieve the minimum profile error in honing of SAE 4320-H steel. Pinion parts were used as workpieces to test the optimization technique. It is determined from optimization that the optimum feed rate in X direction ranged from 1.5 to 5.7 μm/min and the optimum feed rate in Z direction was between 100 and 600 mm/min. The result also showed that the ideal spindle speed was 4000 rpm according to optimization tests. Lawrence et al. [10] studied in plateau honing for the processing of cylinder liners of automotive engine for developing the operating level of honing parameters in rough, finish and plateau honing. Honing experiments were performed on cast iron cylinder liners with different levels of honing process parameters. The results shown that in rough honing stage, rotational speed of 47.14% followed by oscillatory speed of 20.15% while in plateau honing stage, oscillatory speed of 27.44%, pressure of 27.0%, honing time of 17.98% and rotational speed of 13.80% for the final surface topography formation of liners. In a study about plateau-honing by Pawlus et al. [11] diamond abrasive stones were used for honing cast iron cylinders of diesel engines. The different levels of working pressure and plateau-honing time were used in honing experiments while grain size was kept as constant 151, 76 and 15 in rough, semi finish and final plateau operation, respectively. The study makes correlation between roughness parameters related to the Abbott–Firestone curve and the probability curve. They confirmed linear independence and stability of probability parameters.

This research was focused on optimizing of the honing parameters such as linear speed, grain size and number of stroke for surface roughness in the plateau honing of engine block made of cast iron. Firstly, Taguchi method were used to reach this aim. Secondly, the analysis of variance in order to determine the significance level of honing parameters and optimization studies was performed at confidence level of 95%.

2. MATERIALS AND METHOD

2.1 Cutting conditions and equipment

Honing experiments were carried out on a four-cylinder gasoline engine block of cast iron. The honing tools (honing head, honing stone, honing brush) used in the honing of the cylinders were given in Fig. 1.

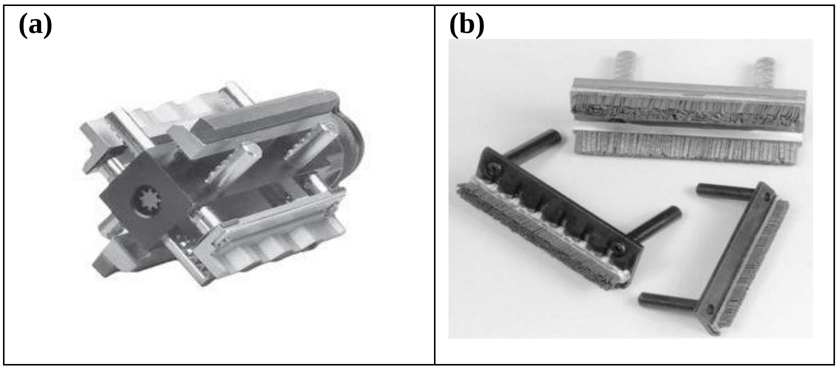

Figure 1. *Honing tools;* ***a)*** *Honing head with honing stone,* ***b)*** *Honing brush*

The honing tool manufactured by Sunnen were obtained from Mikroteknik companies in honing experiments. AN112-coded portable honing head (Fig.1a) was used in order to connect honing stones. Honing processes were carried out in two stages as rough and plateau honing. The honing stones having SiC quality of M27 J45, M27 J55 and M27 J65 coded set of stones and C30PHT731 coded honing brush set were used for rough honing and plateau honing process, respectively. The gas oil (kerosene) was used as honing oil in the experiments that are repeated twice. Experiments were performed in Motorsan Company by using cylindrical rectification machine (Fig.2a) and honing machine (Fig.2b) manufactured in Honmaksan Inc.

The desired surface roughness was obtained by first process (rough honing) and then finish honing in plateau honing. The diameter of cylinders (Ø 79.6 mm) which belong to engine block used in experiments was measured with hole comparator and decreased to 79.55 mm by turning in rectification machine. The honing tolerance was taken as 0.05 mm in honing experiments while it is suggested as 0.04-0.06 mm in the literature [12]. Plateau honing was performed by honing brush after rough honing without changing any honing conditions. The surface roughness occurred during rough and plateau honing were measured (Fig.2c) with Mahr Perthometer M1. The average surface roughness (*Ra*) was determined with regards to honing parameters of cylindrical surfaces. Six measurements of each honing experiment were done and calculated their average for the *Ra*.

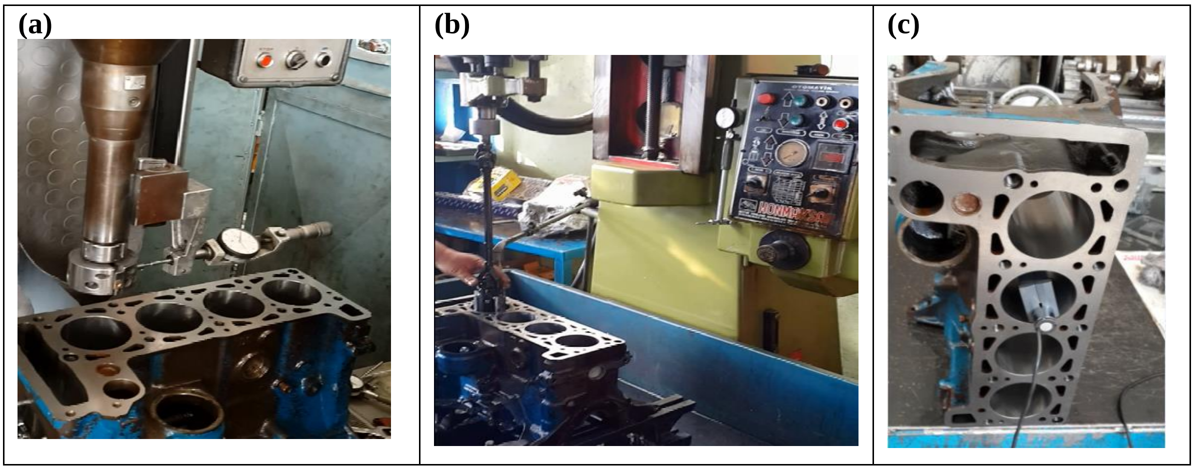

Figure 2. *a) Rectification machine, b) Honing machine, c) Surface roughness measurement*

2.2 Experimental design and optimization

At the first stage of study, the honing parameters directly affected on surface quality in honing process were determined. For this purpose, linear speed (*Vr*), grain size (*Gs*), number of stroke (*S*) were chosen with three different levels depending on recommendation of honing tools manufacturer that is Sunnen. Taguchi L_9 orthogonal array was used as the design of experiment according to these parameters and their levels given in Table 1. The spindle speed of the honing machine is only 80 and 160 rev/min. The honing angle must be adjusted between 30°-90° as mentioned in literature [13]. In this regard, the tangential speed (*Vc*) was chosen as 80 rev/min (Fig. 3) for the honing angle (α) calculated theoretically from Eqn. 1.

Table 1. *Factors and their levels*

Factors	Levels		
	1	*2*	*3*
Vr (m/min)	7	10	13
Gs (mesh)	150	180	220
S	4	6	8

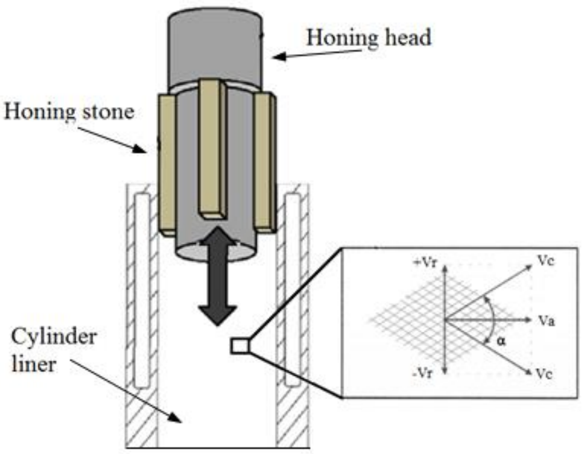

Figure 3. *Schematic view of honing process*

$$\tan(\alpha / 2) = \frac{Vr}{Va} \tag{1}$$

The final stage of Taguchi method is optimization study for surface roughness as quality characteristic. "The smaller the better" method were applied due to desire of minimum average surface roughness during determination of quality characteristic. The experiment conditions giving optimum surface roughness value were determined in optimization according to *S/N* ratio [14].

$$S / N = -10 \cdot \log\left(\frac{1}{n} \cdot \sum_{i=1}^{n} y_i^2\right) \tag{2}$$

Where "*n*" and "*y*" shows the number of experiments and quality characteristic, respectively in Eqn 2. The effect level of parameters on *Ra* were determined according to experimental results with %95 confidence level of analysis of variance (ANOVA). Statistical analyses and optimization studies were performed via Minitab 15 software.

3. RESULTS AND DISCUSSION

The effect of honing parameters (linear speed, grain size and number of stroke) on surface roughness is presented in honing of engine cylinder blocks whose machinability investigated with plateau honing. The total of 9 experiments were conducted according to Taguchi L_9 orthogonal array with respect to parameters controlled in machining processes. The honing parameters were evaluated as independent variables while average surface roughness (*Ra*) were evaluated as dependent variable in this study. Ra should be preferred by particularly companies of engine renewal as a measurement criterion for the quality of the formed surface in honed surfaces.

The assessment of experimental results was done via graphs and statistical analyses with obtained data. The surface roughness values from rough honing experiments and *S/N* ratios calculated by "the smaller the better" method is given in Table 2. Besides, the variation of surface roughness according to linear speed and grain size is illustrated in Fig. 4.

Table 2. *Experimental results and S/N ratios*

Exp. No	*Vr*	*Gs*	*S*	*Ra*	*S/N*
1	1	1	1	1.234	-1.8263
2	1	2	2	0.951	0.4363
3	1	3	3	0.798	1.9599
4	2	1	2	0.987	0.1136
5	2	2	3	0.774	2.2251
6	2	3	1	0.712	2.9504
7	3	1	3	1.103	-0.8515
8	3	2	1	0.902	0.8958
9	3	3	2	0.721	2.8412

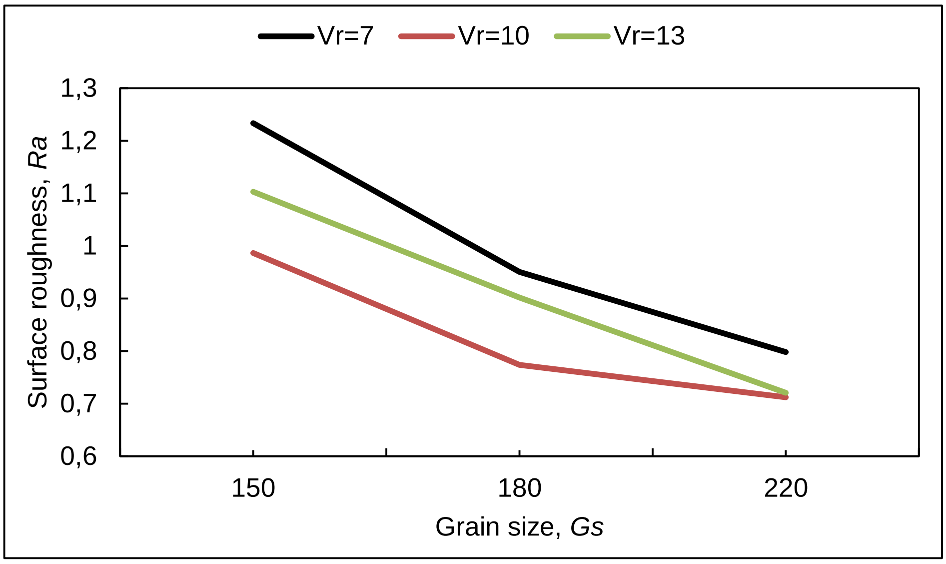

Figure 4. *Variation of Ra versus cutting parameters*

As can be seen from Fig. 4, the average surface roughness decreased with increasing grain size. On the other hand, surface roughness decreased when linear speed increased from 7 m/min to 10 m/min but increased when linear speed increased from 10 m/min to 13 m/min. Therefore, this figure cannot give a specific relationship between surface roughness and linear speed. As a result of rough honing experiments, the smallest surface roughness was determined as 0.712 µm in linear speed of 10 m/min, grain size of 220 and number of strokes of 4 while the highest value was 1.234 µm in linear speed of 7 m/min, grain size of 150 and number of strokes of 4.

The results of ANOVA with 95% confidence level in order to determine the effect level of parameters on *Ra* were given in Table 3. Here, the probability (P) values indicating the importance level of each factor, degree of freedom (*DF*), the sum of squares (*SS*), mean square (*MS*), *F-ratio* and the percent contribution ratio (*PCR*) was shown. The importance level of parameters was determined by considering *P- value* that should be lower than 0.05. Table 3 showed that the most important factor on surface roughness is grain size with 81.04% *PCR*. The secondary important factor on *Ra* is linear speed with 16.77% *PCR*. It was determined from ANOVA results that the number of strokes has no importance on *Ra* in 95% confidence level.

Table 3. *ANOVA results for Ra*

Factor	*DF*	*SS*	*MS*	*F- ratio*	*P- value*	*PCR (%)*
Vr	2	3.7123	1.85613	44.04	0.022	16.77
Gs	2	17.9423	8.97116	212.85	0.005	81.04
S	2	0.4011	0.20054	4.76	0.174	1.81
Error	2	0.0843	0.04215			0.38
Total	8	22.1399				100.00

Due to the fact that optimization of process setting parameters increases the usefulness for process economics in addition to product quality, an attempt were made to define optimal process parameters to generate the best possible surface quality within the experimental restrictions. For this purpose, *S/N* ratios of factors are considered in Taguchi optimization method. The highest *S/N* ratio shows the optimum level of factor according to "smaller is better" approach. *S/N* ratios calculated via experimental results of *Ra* are shown in main effect plots (Fig. 5). Also, the distribution of *S/N* ratios according to factors is given in Table 4. It was shown that grain size is the most important factor on *Ra* when examining the main effect plots in Fig. 5 and difference (Δ) of maximum and minimum values of *S/N* ratios in Table 4. The optimum levels for minimum *Ra* according to *S/N* ratios were determined as *Vr2*, *Gs3* and *S2*.

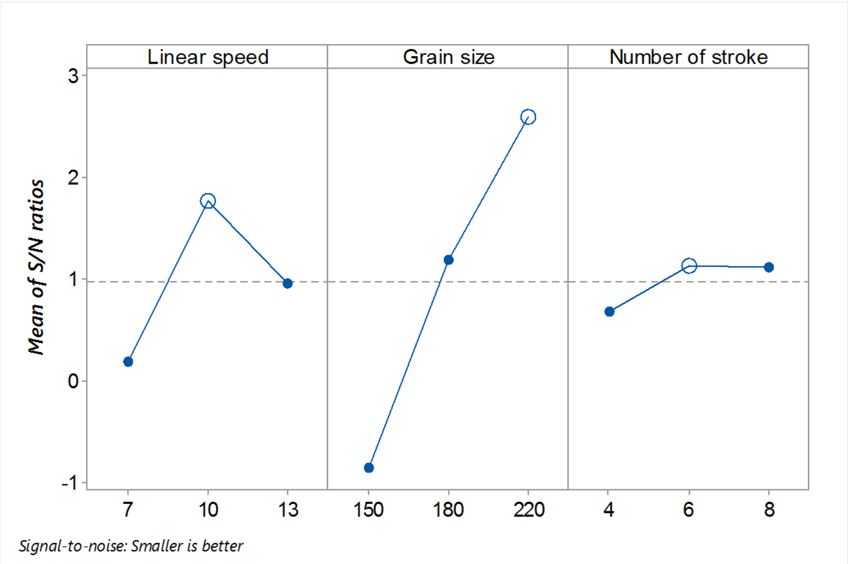

Figure 5. *Main effect plot for S/N ratios of Ra*

Table 4. *Response table of S/N ratios for Ra*

Factors	*S/N* ratios			
	Level 1	*Level 2*	*Level 3*	*Δ*
Vr (m/min)	0.1900	1.7631*	0.9619	1.5731
Gs (mesh)	-0.8547	1.1858	2.5839*	3.4386
S	0.6733	1.1304*	1.1112	0.4571

*Optimum levels of factors

Average of experimental results performed at optimal levels are evaluated by Eq. (3) to forecast the mean for the treatment conditions. Eq. (1) which is the expression of calculated surface roughness (Ra_{cal}) is derived from Eq. (4).

$$\eta_G = \bar{\eta}_G + (\bar{A}_O - \bar{\eta}_G) + (\bar{B}_O - \bar{\eta}_G) + (\bar{C}_O - \bar{\eta}_G) \tag{3}$$

$$Ra_{cal} = 10^{-\eta_G / 20} \tag{4}$$

Where, η_G is the *S/N* ratio calculated at optimal level of factors (dB), $\bar{\eta}_G$ is the mean *S/N* ratio of all factors (dB), $\bar{A}_O$, $\bar{B}_O$ and C_O are the mean *S/N* ratio once linear speed, grain size and number of stroke are at optimum levels, and is the calculated Ra_{cal} value. Consequently, η_G and Ra_{cal} for optimum honing parameters were determined as 3.5334 dB and 0.665 µm, respectively. Lastly, confirmation experiments were performed by using the optimum honing parameters after the determination of these factors for *Ra* and so consistency of the optimization has been confirmed. The experiments conducted by considering the confidence interval (*CI*) calculated from Eq. (5) and (6) [15].

$$CI = \sqrt{F_{\alpha,(1,v_e)} V_e \left(\frac{1}{\eta_{eff}} + \frac{1}{r}\right)} \tag{5}$$

$$n_{eff} = \frac{N}{1 + \upsilon_T} \tag{6}$$

Where; $F_{\alpha(1,\upsilon e)}$ is the *F* ratio at the 95 % significance level, α is the importance level, υe is the degree of freedom of the error, *Ve* is the error variance, n_{eff} is the effective number of replications, *r* is the number of replications for the verification test. In Eq. (6), *N* is the total number of experiments and υ_T is the total main factor of the degree of freedom. Measured surface roughness (Ra_{exp}), calculated surface roughness (Ra_{cal}), and *S/N* ratio (η_{exp}, η_{cal}) for *Ra* are given in Table 5 by comparing between results of experiments and calculated values.

The variances between the values of confirmation experiments and the calculated values by Eq. (3) of the *S/N* ratios. The difference of 0.2091 dB can be seen under than confidence interval of 0.9310 dB for average surface roughness. Thus, the optimum level of machining parameters for *Ra* were confirmed as confident.

Table 5. *Comparison of results*

Experimental result		Calculated value		Difference	
Ra_{exp} (µm)	η_{exp} (dB)	Ra_{cal} (µm)	η_{cal} (dB)	Ra_{exp}-Ra_{cal}	η_{exp}-η_{cal}
0.682	3.3243	0.665	3.5334	0.0163	0.2091

The usage of honing brush set is recommended by manufacturers of honing tools after initial honing to provide a plateau surface on cylinder liners in renewal of motor cylinders. As a final step of the experimental study, plateau honing processes were performed with same honing conditions (linear speed and number of stroke) and Sunnen C30PHT731 honing brush set with constant grain size of 320 [16]. The same experimental procedure in rough honing were also applied for plateau honing processes. Ra values were measured as 0.682 and 0.494 µm in the result of rough and plateau honing by using optimum machining parameters (Fig.6). It is shown that this value from plateau honing is in range of required average surface roughness on cylinder surfaces after renewal of engine as mentioned literature [12].

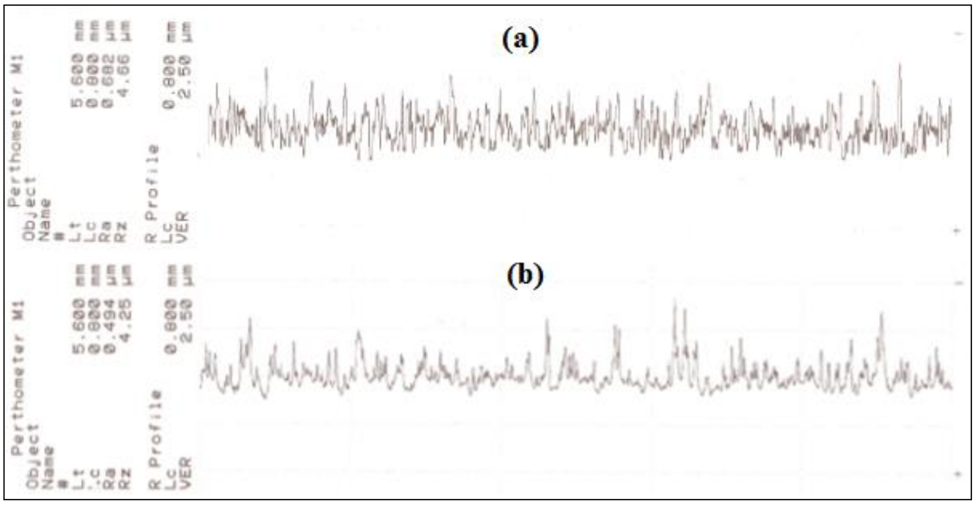

Figure 6. *Roughness profile formed after honing; a) Rough, b) Plateau*

4. CONCLUSION

This study presents optimum levels of the factors on average surface roughness (*Ra*) during honing of four-cylinder gasoline engine block made of cast iron. For this purpose, *Ra* values were determined by honing process performed according to Taguchi L_9 orthogonal array. Besides, the statistical analysis and optimization studies were conducted at confidence level of 95%. According to ANOVA results, the most important factor on surface roughness is grain size with 81.04% *PCR*, following linear speed with 16.77% *PCR*. The number of strokes has no importance on *Ra* in these cutting conditions. Multi objective optimization was used to select the most appropriate honing conditions. The optimum levels of factors were determined as *Vr2, Gs3* and *S2* for minimum surface roughness. Finally, the difference of between confirmation experiments and the calculated values were determined as 2.5%. This shows that the optimal levels of honing parameters for *Ra* were confirmed as confident in renewal of engine cylinders.

ACKNOWLEDGEMENT

This study is supported by Scientific Research Project Unit of Karabük University (KBÜ-BAP-14/1-YL-020) and the authors express their appreciation for this support.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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