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Effect Of Honing Process Parameters On Surface Quality Of Engine Cylinder Liners

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Abstract

The effect of different honing parameters such as honing feed pressures – rough and finish, and peripheral speed of the honing head, on the quality of surface produced in honing of grey cast iron liners of engine cylinder bores is explored. For experimental investigation, diamond tools of grades D126 and D76 were used for rough and finish honing respectively. The roughness parameters Rz (JIS) and Ra have been considered. The standard that has been followed for roughness measurement is JIS 1994. The second-order mathematical model has been developed for Rz and Ra on the basis of the experimental results. The roughness models as well as the significance of the honing parameters have been validated with the analysis of variance (ANOVA). The paper gives information related to the mechanical honing process used in mass production environment. It was observed that mechanical honing can be done effectively with the use of feed pressures variation (in stages) during each step of honing i.e. rough and finish honing to get the quality surface of cylinder liners along with the possible optimum cycle time where cycle time is secondary when compared to the surface quality even in mass production environment.

Keywords: ANOVA; Model fitting; Response Surface Methodology (RSM); Roughness parameters.

1. Introduction

In present scenario, manufacture of internal combustion engines is a competitive exercise in which high volumes and tight profit margins exert a continued pressure to drive down unit production costs along with the production of engines which should have characteristics such as lower friction, reduced wear and hence longer life [1]. Cylinder liner surface finish controls the frictional losses, oil consumption, and emissions of internal combustion engines to a large extent [2]. The requirements of the cylinder liner surface are complex and should provide sufficient surface roughness to resist wear as well as to store and provide oil for lubrication. The roughness parameters like Rz, Ra are used for the functional performance prediction and quality control of cylinder liners.

Interior honing is a machining process in which a tool with abrasive stones fixed on it performs simultaneously both a rotational and reciprocation movement to scrape material from the inside of a cylindrical workpiece, generating a cross-hatch pattern on the workpiece surface [3]. Honing is a low speed sizing and surface finishing process in which material removal is the result of shearing action of the bonded abrasive grains of a honing stone or ledge. In addition to removing material, the most important function of honing process is to generate the specified functional characteristics for surfaces. Functional characteristics generated by honing include geometric accuracy (diametric roundness and straightness), dimensional accuracy (diameter) and surface character (roughness and lay pattern) [4].

Cylinder liners of internal combustion engines can be finished by using two or three step honing process. These two or three step honing processes give cylinder liner, the desired finish and a surface texture with the characteristic cross-hatch groove pattern. In current investigation, two step honing process is considered. The required surface is generated using two-step honing process, the first step is - rough honing using a coarser honing stone (higher grit size) aiming to improve the cylindricity of the bore, generate deep valleys for lubrication retention and also to remove the surface errors that are the result of machining operations before honing like fine boring. The second step is finish honing, which is accomplished using a smaller size abrasive grit on honing stone aiming to produce the final finished surface of required roughness. During rough honing, the deeper grooves will be formed which are very much important for lubrication retention while the shallower grooves will be formed during finish honing which will help in formation of good bearing surface along with the sufficient lubrication retention capability [5].

L. Sabri and S. Mezghani studied the influence of bond material on the output responses of the engine cylinder bore honing process in terms of the surface roughness, MRR and wear properties of stones [1]. Irene Buj-Corral focused on the issue of roughness variability which he has found as a result of the measurement strategy. It was verified that the larger the number of measurement points, the lower the variability in roughness values obtained [2]. Damir S. Vrac studied the influence of honing process parameters on surface roughness and productivity of cast iron cylinder liners machined by mechanical honing for tools of grade D181 and D151 [5]. L. Sabri and M. El Mansori investigated the performance of vitrified bonded diamond (VBD) which is a new type of composite abrasive stone and compared it with vitrified bonded silicon carbide (VBSC) [6].

The paper presents the results on the effect of process parameters on surface roughness (Rz and Ra) for conventionally honed grey cast iron obtained by honing process. The hypothesis is that both rough and finish honing can be done with the concept of pressure variation (staged honing feed pressures) by conventional mechanical honing in order to achieve sufficient surface quality along with the higher productivity [7]**.** The hypothesis was that, during each step of honing, firstly applying the high feed pressure to remove the material with high rate along with the controlled geometrical characteristics (cylindricity, roundness etc.) and then applying smaller pressure for removal of next 5-10 μm material to generate the controlled surface roughness. During rough honing, second pressure will generate a controlled surface for next step i.e. finish honing. During finish honing stage, again two pressures can be applied to achieve the required value of the roughness but with reduced cycle time. The amount of material removed during rough honing is around 30-35 μm and during finish honing the amount of material removed is 10-15 μm. The material removed by second pressure of rough honing stage is around 8-10 μm, while material removal by second pressure of finish honing stage is around 5-7 μm. The final surface formed is nothing but the superimposition of the surfaces formed with rough and finish honing. The workpiece is mounted in a fixture which permits it to float, which results in the self alignment of the tool and workpiece [4].

2. Materials and Methods

2.1 Design of experiments

The design of experiments technique is a very powerful tool, which permits us to carry out the modelling and analysis of the effect of process variables on the response variables [8]. The response variable is an unknown function of the process variables, which are known as design factors. In the present study, the design factors selected are: Rough honing pressure 2 (P2rh), finish honing pressure 2 (P2fh), and Peripheral speed (Vp), while other parameters have been assumed to be constant. The required diameter of the finished cylinder block is 47.008~47.028 mm. In-process air gauging is being used to control diameter during rough honing and finish honing stage. The parameters that were observed to be significant after pre-experimentation are considered for further study [9]. RSM (Response Surface Method) procedure was carried out as follows:

a) 20 numbers of experiments were performed for adequate and reliable measurement of the response of interest.
b) A mathematical model of the second-order response surface with best fit was developed.
c) The direct and interaction effects of the process parameters were represented through direct effects plots and two-dimensional contour plots.

In order to define the experimental region considered, preliminary experiments were carried out to determine narrower, more effective ranges of process parameters before designing the experimental runs.

2.2 Response variables selected

Ra is used to describe the roughness of machined surfaces. It is useful for detecting general variations in overall profile height characteristics and for monitoring an established manufacturing process. Rz is useful for evaluating surface texture, particularly where the presence of high peaks or deep valleys is of functional significance. Rz should be preferred as a measurement criterion for the quality of the produced surface particularly in honed surfaces. Hence, in present study the roughness parameters Rz and Ra have been selected as the response variable.

2.3 Equipment and tools used

Experiments were carried out on a vertical two-spindle honing machine of Gehring make, using a tool with head diameter of φ 60 mm. Rough honing was done using honing stones of D126 grade and finish honing was done using stones of D76 grade. Both the tools were having abrasive stone dimensions of 4x4x100. The abrasive material for both the stones was diamond. During honing, honing oil 'HON7'was used. The temperature of honing oil was maintained in between 25 - 30°C. Hydraulic feed was applied for radial motion of honing stones.

2.4 Workpiece material

The present study was carried out with grey cast iron. The material composition of the workpiece material is shown in Table 1. The microstructure (Figure 1 with 100x magnification and Figure 2 with 500x magnification) consists of pearlitic matrix with graphite flakes of "Type A" distribution; 4-5% free ferrite, phosphide eutectic phase is also present in the matrix around 4-5 %. The hardness of the grey cast iron liner was observed to be equal to around 230 BHN. The chemical composition, microstructure and hardness properties conform to "FG-260" grade as per I.S:210.1978.

2.5 Roughness measurement

Roughness measurements were done using a Mitutoyo Surface Tester SJ 400. Roughness was measured on the inner surface of each cylinder at different positions. A set of 4 points at top, middle and bottom positions of the cylinder liners was measured resulting in 12 measurements per sample [2].

Table 1 Chemical composition of Grey cast iron

Element	%
C	3.14
Mn	0.62
Cr	0.21
Ni	0.05
Mo	0.13
S	0.06
P	0.49
Si	2.1

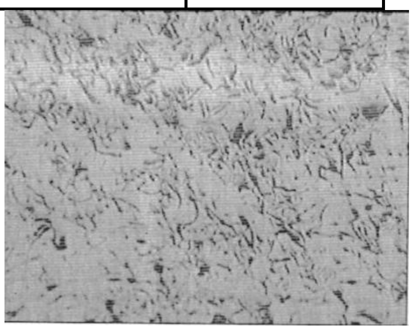

Figure 1 Microstructure of material: 100x

2.6 Experimental conditions

The values of process parameters according to the experiment plan were varied within following limits: Rough honing pressure 2 (P2rh) = 833-1225 kPa, Finish honing pressure 2 (P2fh) = 588-980 kPa, Peripheral speed (Vp) = 32.46-41.31 m/min while the remaining parameters were kept at the following values: Reciprocation speed (Vr) = 18 m/min, Rough honing pressure 1 (P1rh) = 1372 kPa, and Finish honing pressure 1 (P1fh) = 1078 kPa.

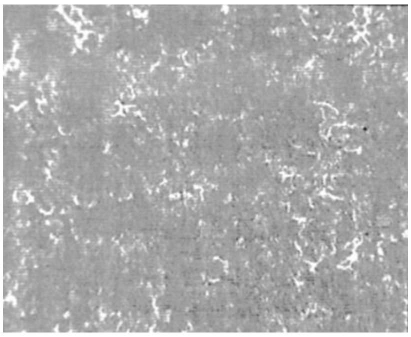

Figure 2 Microstructure of material: 500x

The selection of the levels of the parameters is constrained by the capacity of the machine used in the experimentation as well as the recommended specifications for different workpiece-tool material combination [4].
Table 2 shows the Face centered central composite design matrix.

3. Results and Discussions

The effects of the process parameters on the response parameters selected have been estimated for the grey cast iron cylinder liners by conducting experiments as outlined in section 2. Response Surface Design (Face Centered Central Composite Design) was applied in planning and conducting the experiment. The results are then put into the Minitab software for further analysis. The second-order model was postulated in obtaining the relationship between the surface roughness parameters Rz, Ra and the input process parameters. The analysis of variance (ANOVA) was used to check the adequacy of the second-order model.

Model Fitting:

The results from the 20 honing trials performed as per the experimental plan are shown in Table 2 along with the run order selected at random.

Table 2 Face Centered Central Composite Design

Run Order	P2rh	P2fh	Vp	Rz	Ra
1	1029	784	36.89	3.93	0.67
2	1029	784	36.89	3.86	0.63
3	1225	588	41.31	3.6	0.57
4	1029	784	36.89	3.95	0.64
5	1029	784	32.46	3.99	0.67
6	833	588	41.31	3.21	0.5
7	1029	784	36.89	3.89	0.63
8	1029	784	36.89	3.74	0.61
9	1225	784	36.89	4.11	0.7
10	1029	784	41.31	3.74	0.62
11	1225	980	32.46	4.36	0.71
12	1225	980	41.31	3.87	0.63
13	833	588	32.46	3.48	0.56
14	1225	588	32.46	3.52	0.6
15	833	980	41.31	4.06	0.67
16	1029	588	36.89	3.54	0.58
17	1029	980	36.89	4.03	0.67
18	833	784	36.89	3.73	0.63
19	1029	784	36.89	3.95	0.65
20	833	980	32.46	4.16	0.69

The second-order response surface equations have been fitted using Minitab software for the two response variables, Rz and Ra. The second-order equations in coded units can be given follows:

Rz = 3.88884 + 0.08200*P2rh + 0.31301*P2fh – 0.10300*Vp + 0.02818*$(P2rh)^2$ - 0.10682*$(P2fh)^2$ -0.02693*$(Vp)^2$-0.05250*(P2rh*P2fh)-0.00497* (P2rh*Vp) - 0.05002*(P2fh*Vp)

Ra= 0.644482 + 0.016001* P2rh + 0.056000*P2fh -0.024000*Vp+0.011364*$(P2rh)^2$-0.028636* $(P2fh)^2$ - 0.008663*$(Vp)^2$ - 0.016250*(P2rh*P2fh) - 0.003745*(P2rh*Vp) + 0.001253*(P2fh*Vp)

ANOVA (Analysis of Variance):

Analysis of variance (ANOVA) is employed to test the significance of developed models. The analysis of variance of response surface quadratic model for roughness parameter Rz and Ra were shown in Tables 3, 4, 5 and 6.

The ANOVA have been performed to check the adequacy of the models as well as significance of the individual model coefficients. The ANOVA table for Rz and Ra are presented here. Tables 3 and 5 represent the ANOVA table for individual model coefficients where it can be seen that there are three effects with a P-value less than 0.05 which means that they are significant at 95 % confidence level. These significant effects are Finish honing pressure 2 (P2fh) and Peripheral speed (Vp). P-value for Rough honing pressure 2 (P2rh) is very close to 0.05, thus it may be concluded that P2rh is also significant. Tables 4 and 6 shows the ANOVA table for the second-order model proposed for Rz and Ra respectively. It can be appreciated that the P-value is less than 0.05 which means that the model is significant at 95 % confidence level.

Validation of the models: Graphical tools

It is usually necessary to check the fitted model to ensure it provides an adequate approximation to the real system. Unless, the model shows an adequate fit, proceeding with investigation and optimization of the fitted response is likely to give poor and misleading results [8]. Graphical tools can be used for validation of the models. The graphical method characterizes the nature of residuals of the models. A residual is defined as the difference between an observed value and its fitted value [8]. Figures 3 and 4 show the residual plots for Rz and Ra respectively.

Table 3 ANOVA for Response surface quadratic model of Rz

Term	Coefficient	SE Coefficient	P
Constant	3.88884	0.04105	0.000
P2rh	0.08200	0.03776	0.055
P2fh	0.31301	0.03776	0.000
Vp	-0.10300	0.03776	0.021
P2rh*P2rh	0.02818	0.07201	0.704
P2fh*P2fh	-0.10682	0.07201	0.169
Vp*Vp	-0.02693	0.07201	0.716
P2rh*P2fh	-0.05250	0.04222	0.242
P2rh*Vp	-0.00497	0.04222	0.909
P2fh*Vp	-0.05002	0.04222	0.263

Table 4 ANOVA for second-order model for Rz

Source	DF	Seq SS	Adj SS	F	P
Regression	9	1.25449	1.25449	9.78	0.001
Linear	3	1.15293	1.15309	26.96	0.000
Square	3	0.05930	0.05930	1.39	0.303
Interaction	3	0.04226	0.04226	0.99	0.437
Residual Error	10	0.14259	0.14259		
Lack-of-Fit	5	0.11045	0.11045	3.44	0.101
Pure Error	5	0.03213	0.03213		
Total	19	1.39708			

In the normal probability plot of the residuals shown in figures 3 and 4, the data were plotted against a theoretical normal distribution in such a way that the points should form an approximate straight line, and a departure from this straight line would indicate a departure from a normal distribution, which was used to check the normality distribution of the residuals.

Table 5 ANOVA for Response surface quadratic model of Ra

Term	Coefficient	SE Coefficient	P
Constant	0.644482	0.007746	0.000
P2rh	0.016001	0.007125	0.059
P2fh	0.056000	0.007125	0.000
RPM	-0.024000	0.007125	0.007
P2rh*P2rh	0.011364	0.013587	0.422
P2fh*P2fh	-0.028636	0.013587	0.061
Vp*Vp	-0.008663	0.013587	0.538
P2rh*P2fh	-0.016250	0.007966	0.069
P2rh*Vp	-0.003745	0.007966	0.648
P2fh*Vp	0.001253	0.007966	0.878

Table 6 ANOVA for second-order for Ra

Source	DF	Seq SS	F	P
Regression	9	0.045979	10.06	0.001
Linear	3	0.039675	26.06	0.000
Square	3	0.004067	2.67	0.104
Interaction	3	0.002237	1.47	0.281
Residual Error	10	0.005076		
Lack-of-Fit	5	0.002993	1.44	0.350
Pure Error	5	0.002083		
Total	19	0.051055		

As shown in Figures 3 ad 4, it is reasonable that the assumptions of normality were satisfied for the data. The plots of residuals versus the fitted values and residuals versus the order of the data indicated no obvious pattern, implying that residuals of the models were randomly distributed. As well, the histogram of residuals has shown the normal distribution for Ra but little bit skewed for Rz.

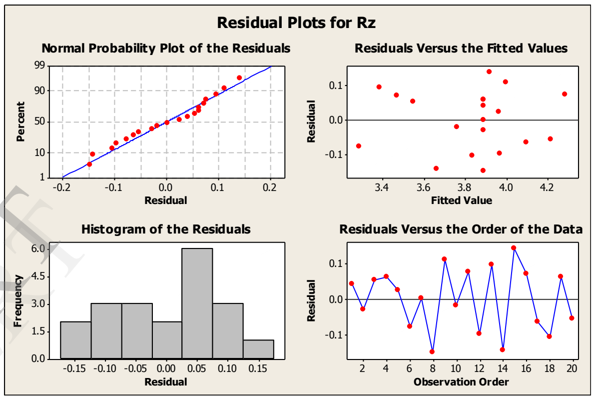

Figure 3. Residual plots for Rz

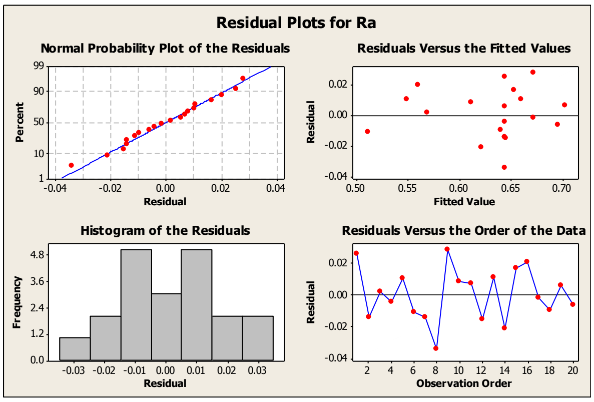

Figure 4. Residual plots for Ra

Effects of process parameters on surface roughness (Rz and Ra):

The main effects of process parameters on output response, surface roughness are shown in Figures 5 and 6. It can be seen from Figures 5 and 6 that P2fh has a huge impact on roughness values (Rz and Ra) and then comes the Vp and P2rh. Figures 5 and 6 shows that Vp at low level yields high roughness value and P2fh and P2rh at low level yields low roughness value. The graph shows the specific trends for P2fh and P2rh i.e. increase in both the pressures results in increase of Rz and Ra value. The rate of increase of Rz and Ra for P2fh from 588 to 784 kPa and 784 to 980 kPa is nearly same. But, for P2rh, the rate of increase of Rz and Ra for P2rh from 833 to 1029 kPa is lower as compared to P2rh from 1029-1225 kPa. Similarly, for Peripheral speed (Vp), the rate of decrease of Rz and Ra values follows the same pattern as that of P2rh. Hence, it can be concluded from main effects plots that with increase in P2fh, Rz and Ra value are increasing with nearly same rate of increase. But, for P2rh the rate of increase is higher initially but it is lower for change of P2rh from 1029 kPa to 1225 kPa. The same trend is followed by V_p as that of P2rh but in reverse manner i.e. the rate of decrease of Rz for change of Vp from 32.46 to 36.89 shown a lower rate of decrease of Rz and Ra value when compared to rate of decrease of Rz and Ra for Vp from 36.89 to 41.31 m/min.

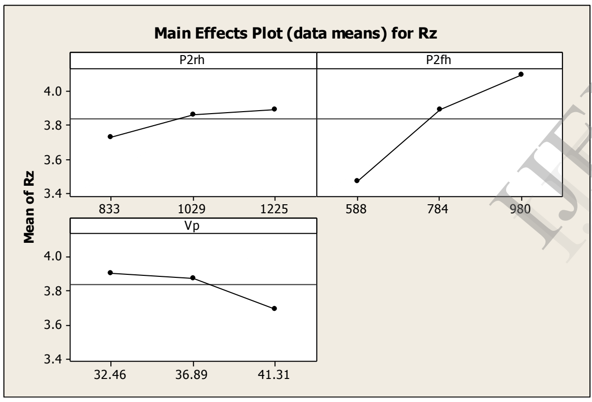

Figure 5. Main effects plot for Rz

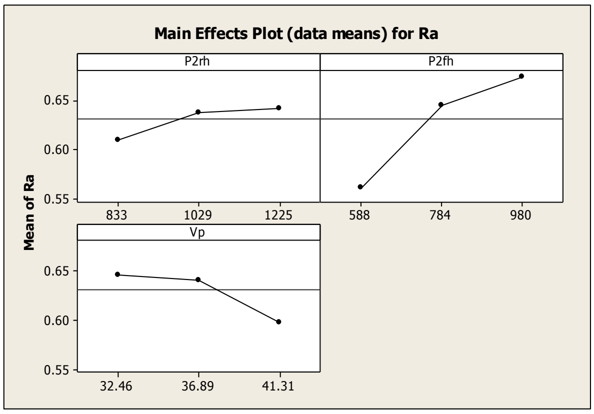

Figure 6. Main effects plot for Ra

Figures 7, 8, and 9 shows the 2-D contour plots for Rz. The contour plots are the graphical representation of the regression equation used to visualize the relationship between the response and experimental levels of each factor. As shown in these plots, increased Rz value was observed with increasing P2fh, P2rh while decreased Rz value was observed with increasing RPM. The contour plots indicates the different regions that are the result of the input values and with the use of these contour plots the prediction of the Rz values can be done effectively.

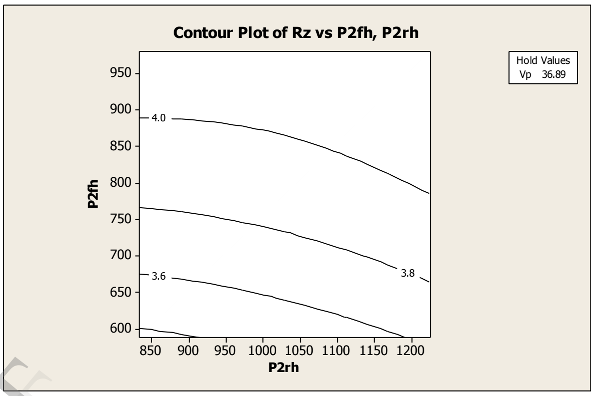

Figure 7. Contour plots for Rz

Figures 10, 11 and 12 shows the 2-D contour plots for Ra, respectively. As shown in these plots, increased Ra value was observed with increasing P2fh, P2rh while decreased Ra value was observed with increasing Vp. The contour plots indicates the different regions that are the result of the input values and with the use of these contour plots the prediction of the Ra values can be done effectively.

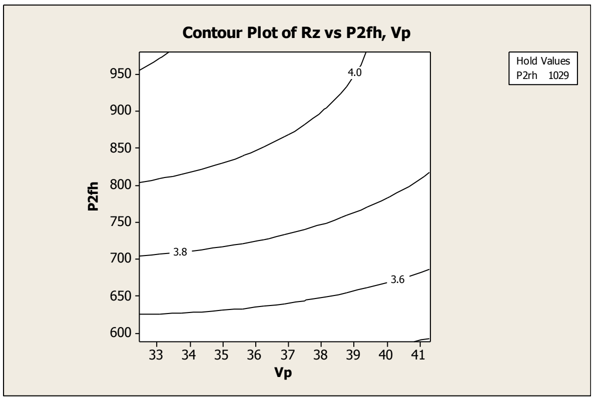

Figure 8. Contour plots for Rz

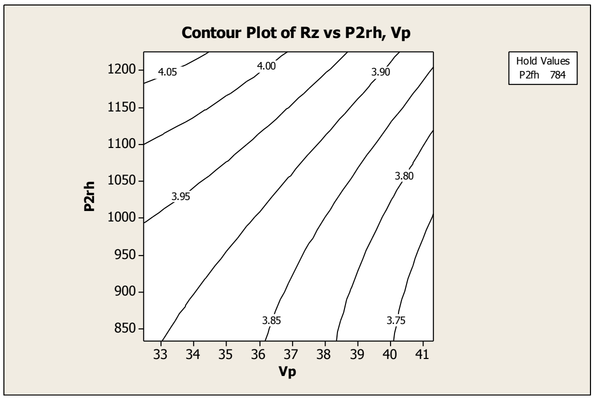

Figure 9. Contour plots for Rz

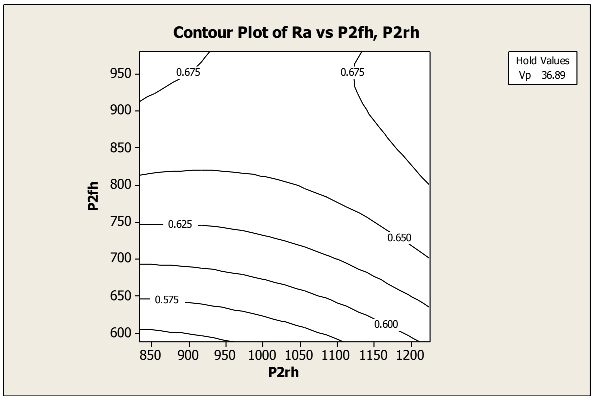

Figure 10. Contour plots for Ra

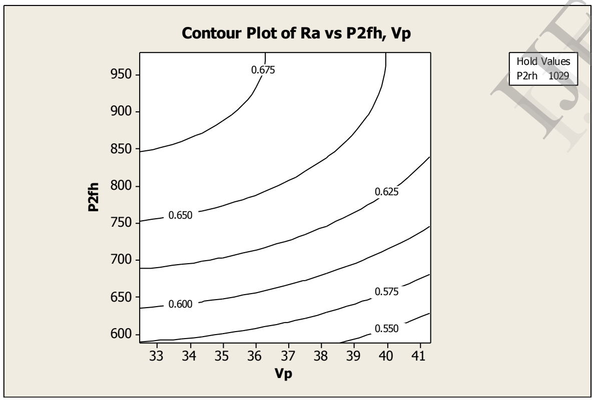

Figure 11. Contour plots for Ra

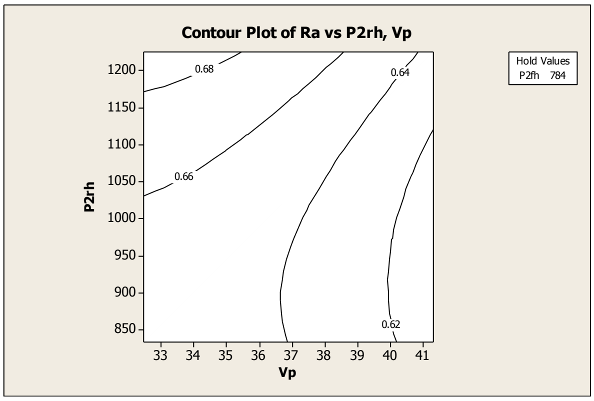

Figure 12. Contour plots for Ra

Finally, since optimization of process setting parameters increases the utility for process economics as well as product quality, an effort has been made to estimate the optimum process parameters conditions to produce the best possible surface quality within the experimental constraints. In this context, a response surface optimization is attempted using Minitab software for the two roughness parameters in combination. The objective function for optimization was set to achieve the target values of Rz and Ra which are targeted at 4.00 and 0.7, respectively. Table 7 shows the RSM optimization results for the roughness parameters. It also includes the results from the confirmation experiments conducted with the optimum conditions. It is found that the error in prediction of the optimum conditions for roughness parameters Rz and Ra is about 2.68 and 4.30 % respectively. Thus, it can be concluded that the response optimization predicts the optimum conditions fairly well.

Table 7. RSM optimization results

Parameters		Rz	Ra
Objective function		Target 4.00	Target 0.70
Optimum Condition	P2rh	1225	1225
	P2fh	737.27	737.27
	Vp	32.46	32.46
Predicted response		4.00	0.6795
Experimental value		4.11	0.71
Error %		2.68	4.30

Table 8 shows the experimental and calculated values of Rz and Ra.

Table 8. Experimental and calculated values of Rz and Ra

Trial No.	Rz		Ra	
	Experimental	Calculated	Experimental	Calculated
1	3.93	3.88873	0.67	0.644455
2	3.86	3.88873	0.63	0.644455
3	3.6	3.54681	0.57	0.568304
4	3.95	3.88873	0.64	0.644455
5	3.99	3.96491	0.67	0.659818
6	3.21	3.28775	0.5	0.511292
7	3.89	3.88873	0.63	0.644455
8	3.74	3.88873	0.61	0.644455
9	4.11	3.9989	0.7	0.671815
10	3.74	3.75891	0.62	0.611818

11	4.36	4.28377	0.71	0.703294
12	3.87	3.9678	0.63	0.645299
13	3.48	3.38377	0.56	0.549297
14	3.52	3.66271	0.6	0.621288
15	4.06	3.91873	0.67	0.653286
16	3.54	3.46895	0.58	0.559819
17	4.03	4.09486	0.67	0.671817
18	3.73	3.83491	0.63	0.639822
19	3.95	3.88873	0.65	0.644455
20	4.16	4.21483	0.69	0.696303

Table 9 shows the obtained limits with 95% Confidence Interval.

Table 9. Obtained limits with 95% Confidence Interval

Trial No.	Rz		Ra	
	Minimum	Maximum	Minimum	Maximum
1	3.79726	3.98019	0.627196	0.661713
2	3.79726	3.98019	0.627196	0.661713
3	3.30987	3.78375	0.523598	0.613011
4	3.79726	3.98019	0.627196	0.661713
5	3.77849	4.15133	0.624644	0.694992
6	3.05081	3.52469	0.466585	0.555999
7	3.79726	3.98019	0.627196	0.661713
8	3.79726	3.98019	0.627196	0.661713
9	3.81249	4.18532	0.636641	0.706989
10	3.57249	3.94533	0.576644	0.646992
11	4.0468	4.52075	0.658581	0.748008
12	3.73086	4.20474	0.600592	0.690006
13	3.1468	3.62075	0.504583	0.59401
14	3.42574	3.89969	0.576574	0.666001
15	3.68179	4.15567	0.608579	0.697993
16	3.28254	3.65537	0.524645	0.594993
17	3.90845	4.28128	0.636643	0.706991
18	3.6485	4.02133	0.604648	0.674995
19	3.79726	3.98019	0.627196	0.661713
20	3.97786	4.45181	0.65159	0.741017

4. Conclusions

This work has demonstrated the application of RSM (Response Surface Methodology) in seeking optimal conditions for honing process setting parameters. The present study develops roughness models for two different roughness parameters for the work material of grey cast iron. The second-order response models have been validated with statistical analyses. It is found that the three parameters (P2fh, P2rh and Vp) have significant effect on roughness parameters considered in the present study. In order to gain a better understanding of the honing process, setting parameters were presented as 2-D contour graphs. Finally, an attempt has been made to estimate the optimum process setting parameters conditions to produce the best possible surface quality within the experimental constraints. The following conclusions were obtained:

1) From statistical analyses, it is clear that the three process setting parameters, P2fh, P2rh and Vp have significant effects on the roughness parameter values.
2) The analysis of variance proved that the most influential parameters on Rz and Ra are P2fh and Vp. While P2rh is least significant as compared to P2fh and Vp.
3) Honing angles are between 46° and 57° for samples honed with the mentioned input parameters.
4) The initial hypothesis that, both rough and finish honing can be done by conventional mechanical honing with the concept of pressure variation during each step of honing process while getting required surface quality, proved to be true.
5) Optimum set of process parameters for Rz and Ra are tested by confirmation experiments and shown fairly good agreement with prediction of the response surface model.

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