Optimisation of honing process parameters for reducing surface roughness and power consumption on grey cast iron (FG-260I)

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Abstract: Optimisation of cylinder liner surface characteristics is being done in honing process for (FG-260I) grey cast iron. Response surface methodology (RSM) and design of experiment (L54) has been used with six input variables to conduct the experiments. The parameters influencing the surface finish and corresponding power consumptions were selected on the basis of available extent literature. Second order RSM approach has been applied to develop a suitable model in honing process having six inputs and single output parameters (R_a). The significant effect of input parameters on surface roughness with corresponding power consumptions has been analysed using combined effort of RSM modelling and analysis of variance (ANOVA). The RSM modelling for the honing process on FG-260I gives significant correlation coefficient (R^2) of 96.7% and adjusted correlation coefficient $(R_{adj})^2$ 96.5 %. The minimum surface roughness has been found by optimal parametric combinations using root mean square error (RMSE) approach. The optimised process parameters will yield acceptable surface finish at least power consumption.

Keywords: honing process; surface finish; FG-260I; response surface methodology; RSM; analysis of variance; ANOVA; root mean square error; RMSE.

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1 Introduction

Honing is an important fine finishing machining process, often, used for internal cylindrical surfaces such as gun barrels, hydraulic cylinders, bearings and engine cylinder bores. Excess material is removed by means of slow moving abrasive sticks pressed against the surface to be machined. Two kind of motions namely rotational and reciprocating are imparted by the honing machine to the hone (or honing tool) carrying the abrasive sticks. Honing is a fine finishing operation, designed to remove surface flaws such as indentations, tapering, out-of-roundness, bowing, etc. Therefore not much material is removed from the component. The machining depth is limited to just a few microns. Suitable cutting fluids (coolants) are used during the honing process to resist the thermal distortion of the work piece. The chips produced during honing are larger than those produced during grinding, because the abrasive grains are in contact with the work piece for the major portion of the stroke. Bartarya and Choudhury (2002) studied the effect of cutting parameters on cutting force and surface roughness during super finishing of hard steel. The cutting speed and feed have to be carefully selected to ensure self dressing action on the abrasive sticks and to avoid their glazing. Surface quality is crucial to the performance of mating parts which have to move relative to each other during service conditions. Examples of such components include connecting rods, piston pins, shafts, bearings and engine cylinders. The automobile industry alone needs such components in ever large numbers. Traditional centre line average R_a has been commonly used to measure the surface quality. However, recent studies have shown that specification of a single R_a value is inadequate to completely characterise the complex surface roughness profile, especially, when questions such as contact area, contact mechanics, lubricant retention, and wear become important (Malburg and Raja, 1993; Bernados and Vosniako, 2002). Many attempts that have been made to develop a variety of techniques for surface finishing through diverse machining processes and many attempts to model the processes and optimise the process parameters. It was analysed the effect of cutting conditions and tool geometry on surface roughness by regression analysis (Allen and Man, 1982; Wang and Chang, 2004).

Surface roughness models were built using response surface methodology (RSM) and experimental results. This method propagates the error information at the output units back to the hidden units using a generalised delta rule (Montgomery, 1991). Artificial neural network (ANN) usually requires very bulk experimental data to train and validate the models (Rumelhart and McClelland, 1986). It was analysed the power expenditure and the surface roughness of the work piece during external cylindrical grinding of a hardened steel part using RSM, which requires only few experimental data (Kwak et al., 2005). A grinding wheel of diameter 320 mm and width 38 mm was used for conducting experiments on chrome-molybdenum steel which was heat-treated to R_c 60. The factors considered as affecting the power output and surface finish included rotational speed of the work piece (rpm), depth of cut (µm), and the traverse speed (m/min). RSM is being concluded as the best suited modelling tool applicable for the honing of cylinder liner. The surfaces finish analysis is also a big issue in the process optimisation of honing of cylinder liner (Staut, 1984). It has reviewed the prediction of surface roughness in machining processes (Bernados and Vosniako, 2003). They discussed the different methodologies and a strategy usually adopted to predict the surface roughness in different machining processes, based on their study, the atomic force microscopy (AFM) is one of the best suitable instruments through which very precised values (nanometres level) of surface finish is calculated among the different techniques used to surface finish measurements.

Figure 1 Honing head with tooling (see online version for colours)

Honing process performed on FG-260I (grey cost iron) bike cylinder liner using L54 array RSM design of experiment having six input variables. The suitable surface finish and corresponding power consumptions influencing parameters were selected on the basis of available literature. Second order RSM extant or extent technique has been used to generate the models. Second order RSM has been used for surface finish modelling where independent process variables are: fluid pressure, temperature of honing environment, grit size, hone angle, circumferential speed and honing time. The optimum process parameters are essential to achieve better surface finish with adequate power consumption per unit time (watt). A lot of research techniques have been reported for response optimisation but present work uses the sum of root mean square error (SRMSE) approach and has achieved an improvement of more than 39.4% in surface smoothness under honing process. The concept of honing machine and setup is illustrated in Figure 1. In the rest of the paper, section provides the experimental setup followed by experimental investigation. Results and discussion are provided in Section 4 and concluded in Section 5. The paper ends with references.

2 Experimental setup

2.1 Selection of parameters and work piece materials

In the present investigation, the honing experiments have been conducted on 56 mm diameter of Yamaha motorcycles cylinder liner. FG-260I (grey cast iron) is used as the material of construction of the cylinder liner. Work piece material was normalised and shot blasted. The chemical composition of the work piece material is: C (3.14), Mn (0.62), Cr (0.22), Ni (0.05), Mo (0.13), S (0.06), P (0.49) and Si (2.1) percentage wise respectively.

Figure 2 R_a measurement of FG-260I by AFM (see online version for colours)

The experiments are being run on a CNC operated honing machine, model HONSD, SL NO-210, (F: 08: 0023: 02) having the facilities to hold the work piece within the place provided by the help of a fixture. Present experiments are aimed at considering significant effects of several controllable and independent parameters on surface roughness of FG-260I during honing. The requirement of surface finish and power consumption are the key factors while selecting a particular combination of input factors. Coarse grits remove high stock of material and are suitable for rough honing (A.E. Goetze GmBH, 1993). Table 1 shows the relationship between grit number and grit particle size (Boothryod and Knight, 1989). Apart from controllable and independent variables (Table 2), there are many parameters which are kept constant as mentioned in

Table 3. Experiments have been carried out randomly using suitable Table 4, so that the repetitions of the runs are not done throughout. AFM is used for surface finish measurement which is having least count of 1 nm.

Table 1 Grit size (μm) and corresponding grit numbers

Grit no.	36	54	80	120	220	320	400	500	600
Size (μm)	710	430	266	142	66	32	23	16	8

Table 2 DOE – levels of the variables

Factor level	*Grit size (μm)*	*Temperature (°C)*	*Speed (rpm)*	*Hone angle θ_H (degree)*	*Flushing fluid pressure, P_F* bar	*Time (in seconds)*
1	30.5	-5	300	0	1.5	15
2	43	10	600	20	4.0	30
3	55.5	25	900	40	6.5	45
4	68	40	1,200	60	9.0	60
5	80.5	55	1,500	80	11.5	75

Table 3 Constant factors during honing

Factors	*Constant values (coded)*
Jog feed	2
Low jog	7
Linear speed	4
Sensitivity	6

Table 4 Experimental observation: FG 260I – second set of readings

SL	*Grit size (μm)*	*Environmental temp. (°C)*	*Rotational speed (RPM)*	*Hone angle (deg.)*	*Fluid pressure (bar)*	*Honing time (sec.)*	*Ra (nm) obs.*	*Ra (nm) pred.*	*Power (watt)*
1	43	40	600	60	9	60	371	363.991294	2.1
2	68	10	600	20	4	60	500	503.786731	3.9
3	68	10	600	20	9	30	555	565.286731	4
4	43	10	1,200	60	4	30	323	268.134349	1.8
5	68	10	600	60	4	30	452	487.423891	3.2
6	43	10	600	20	4	30	489	491.929804	2
7	43	40	1,200	20	4	30	338	354.739719	2.5
8	55.5	25	900	40	6.5	45	414	421.360586	3.4
9	55.5	25	900	40	6.5	45	404	421.360586	3.4
10	55.5	25	900	40	6.5	45	419	421.360586	3.3
11	68	40	600	60	4	60	548	471.081021	4.2
12	68	10	1,200	20	4	30	489	512.748425	3.3
13	68	10	1,200	60	9	30	451	454.786731	3.6
14	68	10	1,200	20	9	60	538	537.953595	4.1
15	43	40	1,200	20	9	60	325	289.529703	2.5

Table 4 Experimental observation: FG 260I – second set of readings (continued)

SL	*Grit size (μm)*	*Environmental temp. (°C)*	*Rotational speed (RPM)*	*Hone angle (deg.)*	*Fluid pressure (bar)*	*Honing time (sec.)*	*Ra (nm) obs.*	*Ra (nm) pred.*	*Power (watt)*
16	68	40	600	20	4	30	401	452.811466	3.6
17	68	40	1,200	60	9	60	566	584.493291	4.6
18	43	10	1,200	60	9	60	344	300.76636	2.9
19	68	10	1,200	60	4	60	426	436.286731	3.1
20	55.5	25	900	40	6.5	45	389	421.360586	2.6
21	68	40	600	60	9	30	570	528.899203	4.3
22	55.5	25	900	40	6.5	45	398	421.360586	3.2
23	68	40	1,200	20	9	30	586	598.723736	3.8
24	55.5	25	900	40	6.5	45	409	421.360586	3.2
25	55.5	25	900	40	6.5	45	421	421.360586	3.2
26	43	10	600	20	9	60	436	427.061815	2.3
27	43	10	1,200	20	9	30	373	437.435468	1.9
28	68	40	600	20	4	60	375	405.073469	3.7
29	68	40	600	20	9	30	465	516.391651	3.2
30	43	10	600	60	9	30	474	492.397059	2.1
31	43	10	600	60	9	60	401	434.286417	3.7
32	43	10	600	60	4	60	358	321.760695	2.5
33	68	40	1,200	60	4	60	479	473.800742	3.4
34	43	10	1,200	20	4	60	202	202.799105	2.8
35	55.5	25	900	40	6.5	45	384	421.360586	3.2
36	68	40	600	20	9	60	396	428.516018	3.7
37	68	40	1,200	60	9	30	513	542.118924	2.8
38	68	40	600	60	4	30	379	445.858665	2.8
39	68	40	1,200	20	4	60	491	476.905554	3
40	68	40	1,200	60	4	30	478	458.288739	2.7
41	55.5	25	900	40	6.5	15	611	591.140082	1
42	55.5	25	900	0	6.5	45	689	633.780867	2.4
43	55.5	25	1,500	40	6.5	45	310	362.371776	2.5
44	55.5	55	900	40	6.5	45	382	397.015764	2.4
45	55.5	25	900	40	1.5	45	268	332.912809	2.3
46	55.5	25	900	40	6.5	45	398	421.360586	2.4
47	30.5	25	900	40	6.5	45	175	241.711468	2.1
48	80.5	25	900	40	6.5	45	763	697.009705	5.2
49	55.5	25	900	40	6.5	45	412	421.360586	2.3
50	55.5	25	900	80	6.5	45	372	386.940305	2.4
51	55.5	25	900	40	6.5	75	337	363.581091	3.3
52	55.5	25	300	40	6.5	45	600	562.349396	2.2
53	55.5	25	900	40	11.5	45	523	509.808364	2.1
54	55.5	–5	900	40	6.5	45	315	361.705409	1.9

2.2 RSM algorithms

RSM has been reported on the development of second order multiple regressions (SOMR) (Witten and Frank, 2001). It would have its own input and output characteristics, and therefore it can only be applied for modelling of some specific honing processes.

$$SR = -4.7766\theta_H + 0.05448 * \text{rpm} - 0.00775 * \mu\text{m} - 0.00538 * {}^\circ\text{C} + 0.000671 * \text{second} - 0.000947 * \text{bar} \quad (1)$$

3 Experimental investigation

Correlation coefficient (R^2) of observed and predicted R_a: the correlation between observed and predicted R_a is very close which indicates the adequate modelling done (Figure 4). Three different models were constructed, but the second model was the best performing one than the other two which is shown plotted in Figures 3 to 5. Residual verses vs. fit plot are being given to understand the deviation from the mean values which is given in Figure 6. Figure 4 indicates the relationship between the observed and predicted correlation coefficient (R^2) is 0.967 which gives excellent result.

Figure 3 Predictions against observations of R_a for model-M2-FG260I (see online version for colours)

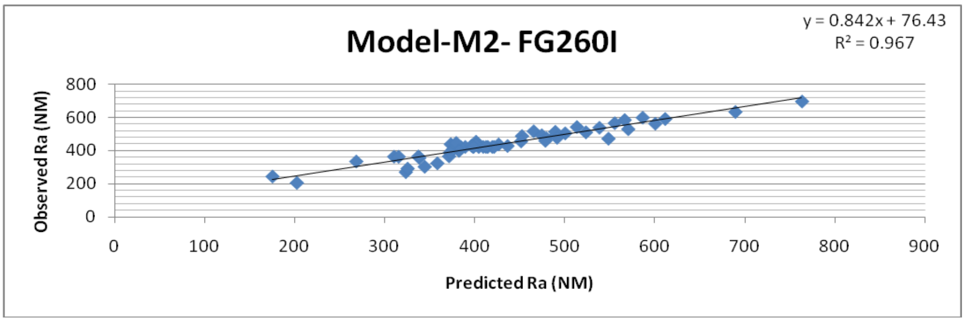


Figure 4 Predictions against observations of R_a for model-M1-FG 260I (see online version for colours)

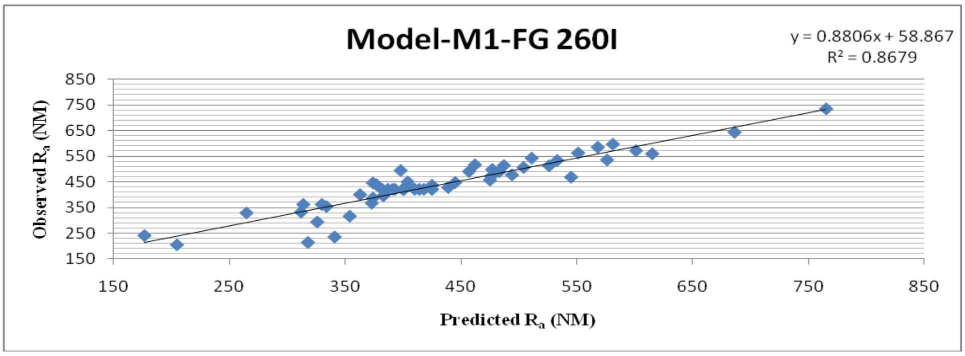


Figure 5 Predictions against observations of R_a for model-M3-FG260I (see online version for colours)

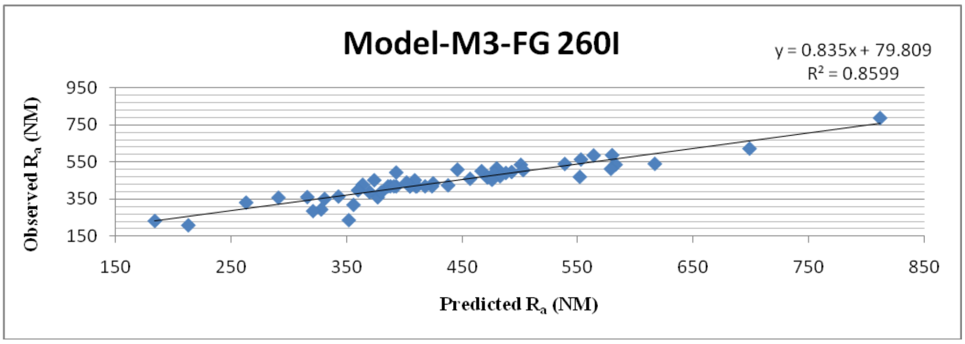


Figure 6 Residual vs. fit for R_a for model-M3, FG-260I (see online version for colours)

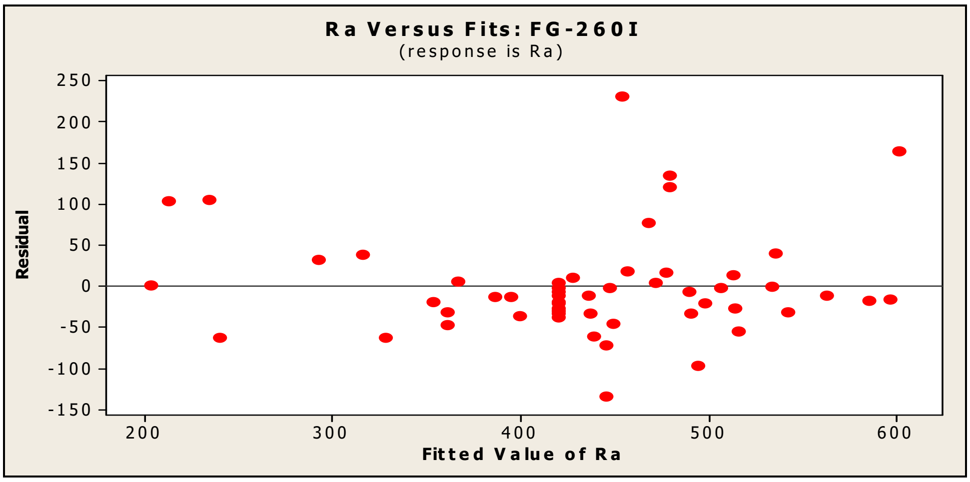
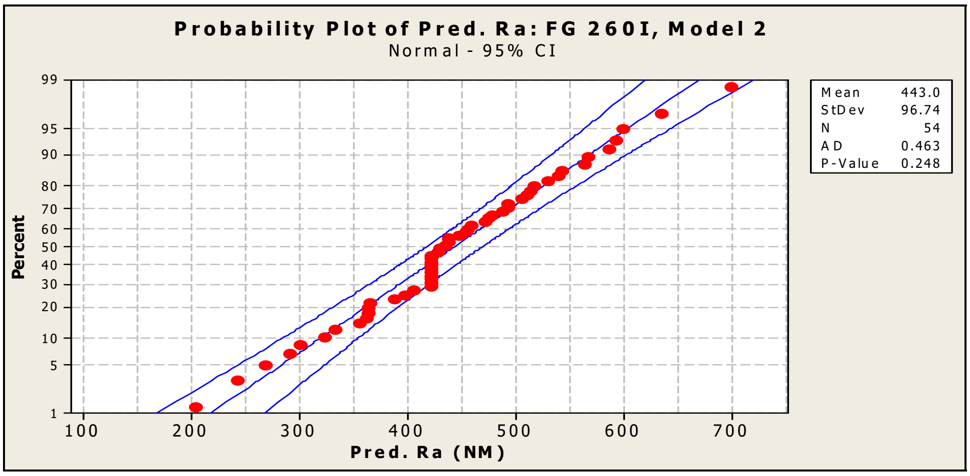


Figure 7 Probability plot of R_a (pred.): FG 260I, model 2 (see online version for colours)



Predicted surface finish data is used to analyse the interactions of factors, interaction plots are being constructed in Figure 9 which indicate the variation of surface roughness depending on individual factors. It is also evident that the factors are found significant as per the ANOVA test at 95% confidence level significantly as given in Figures 6 and 7 consequently. Figures 7 and 8 indicating indicate the probability plot of the predicted responses which are significant.

Figure 8 Probability plot of power cons. (watt): FG 260I, model 2 (see online version for colours)

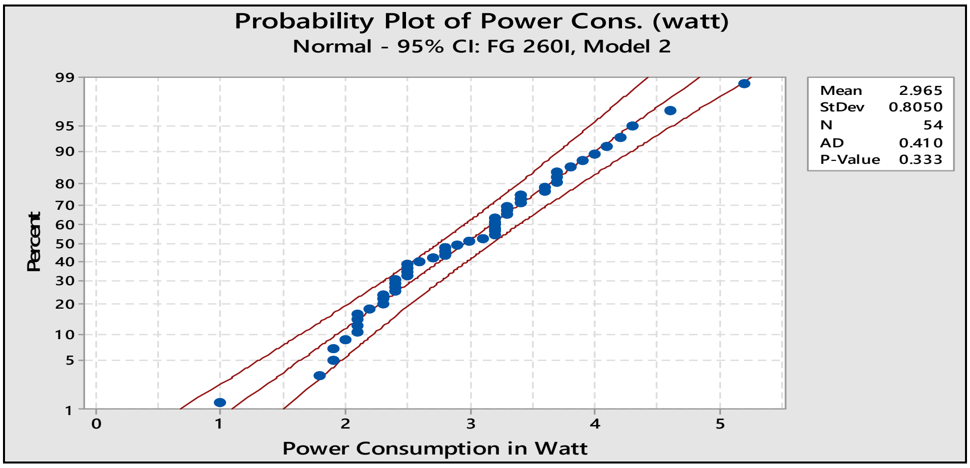
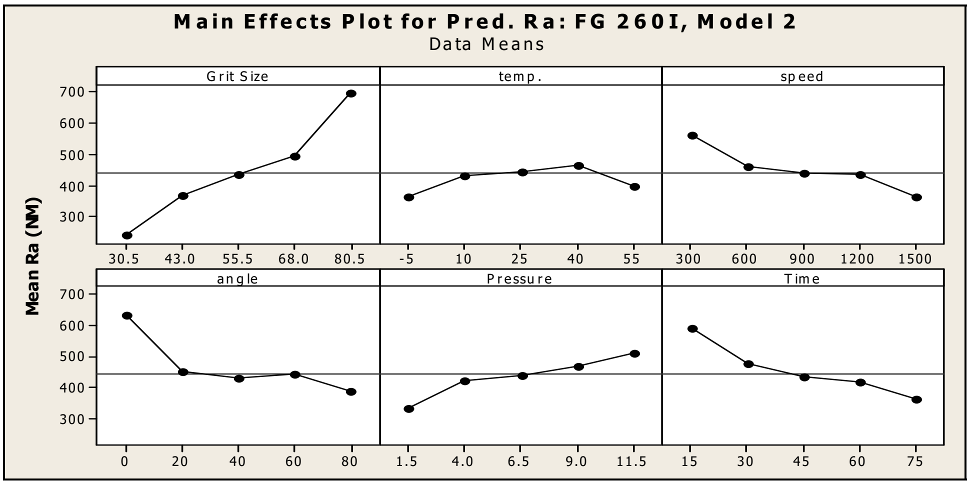


Figure 9 Individual parametric interaction plot of R_a (Pred.): FG 260I, Model 2 (see online version for colours)



Optimisation of surface roughness is being done individually using the root mean square error approach which is indicated in Figures 10 to 15 respectively. The Minitab 16 is used to draw the figures for the optimisation. Each figure indicates the most optimal points having the minimum possible surface roughness at possible corresponding power consumption.

Figure 10 3D plot of R_a (pred.) vs. power cons. with grit size: FG 260I, model 2 (see online version for colours)

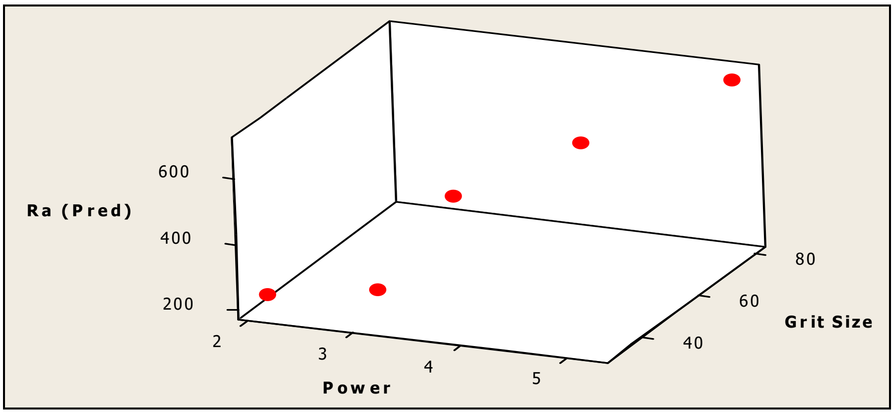


Figure 11 3D plot of R_a (pred.) vs. power cons. with env. temp.: FG 260I, model 2 (see online version for colours)

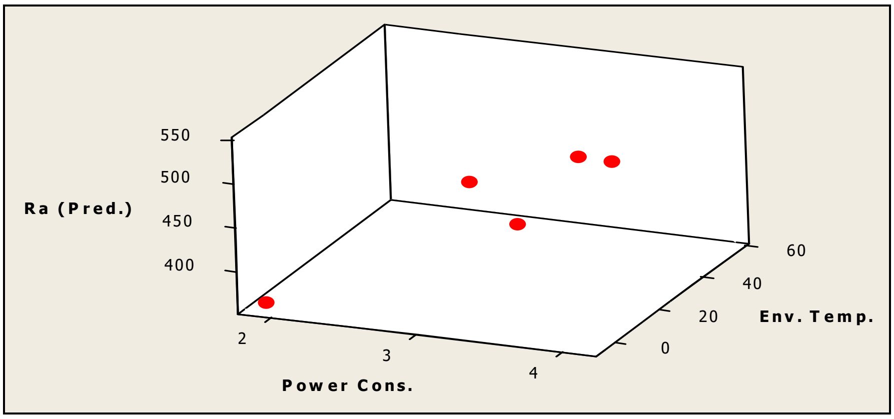


Figure 12 3D plot of R_a (pred.) vs. power cons. with speed: FG 260I, model 2 (see online version for colours)

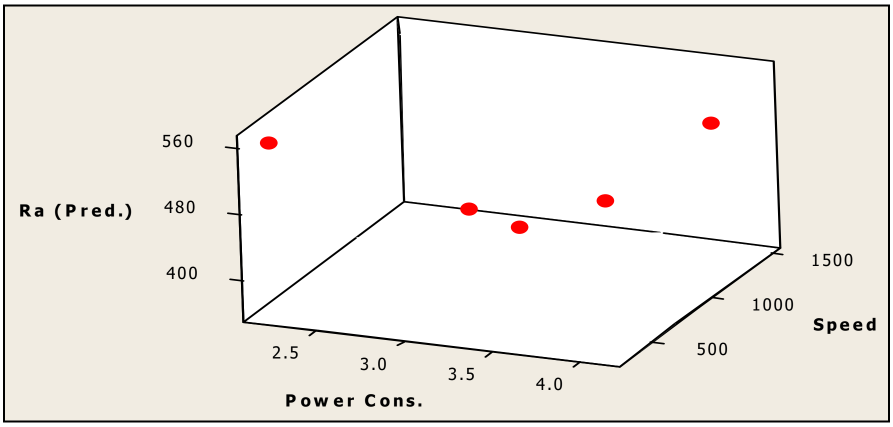


Figure 13 3D plot of R_a (pred.) vs. power cons. with hone angle: FG 260I, model 2 (see online version for colours)

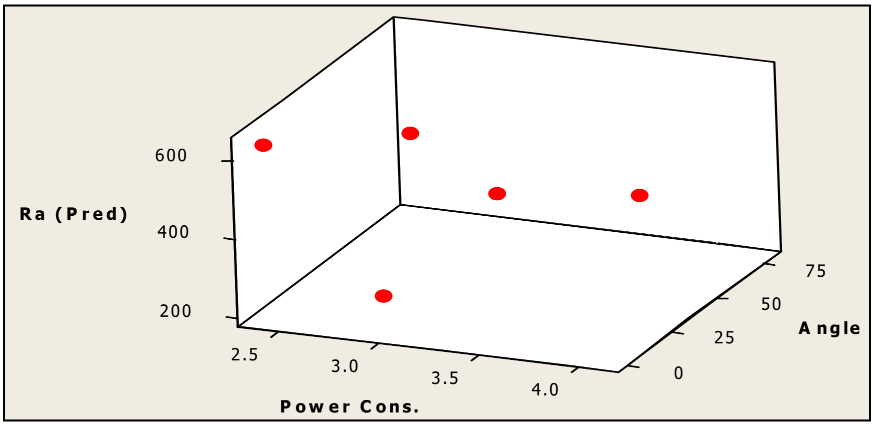


Figure 14 3D plot of R_a (pred.) vs. power cons. with fluid pressure: FG 260I, model 2 (see online version for colours)

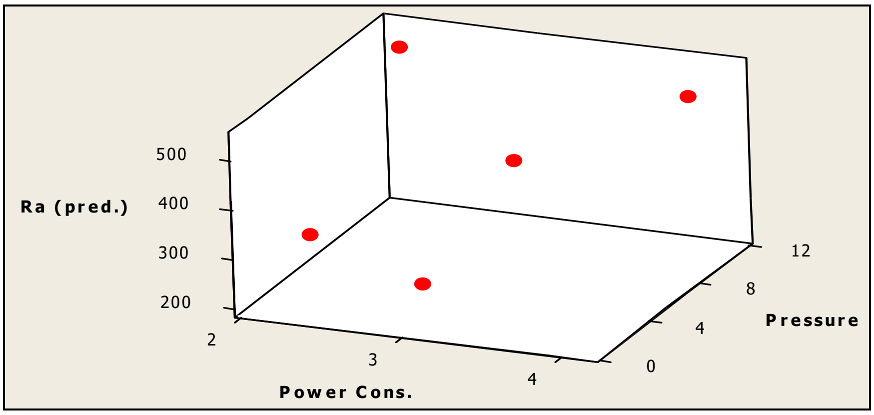
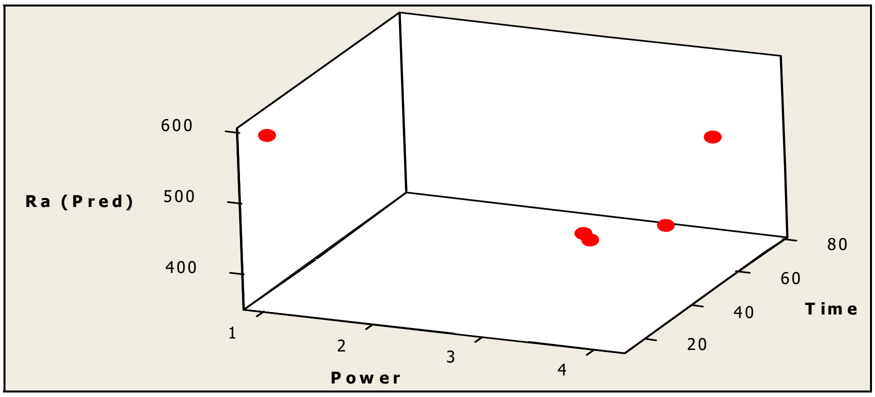


Figure 15 3D plot of R_a (pred.) vs. power cons. with hone time: FG 260i, model 2 (see online version for colours)



It has been indicated from RMSE manual method that the surface roughness will be optimum at the values of individual parametric combinations of grit size, environment temperature, rotational speed, hone angle, and fluid pressure, and honing time is 43, –5, 1200, 60, 4 and 75 respectively.

Table 5 indicates nested ANOVA for surface roughness and it shows that all the six input factors have significant interaction with each other. P-values of each factor indicates the best interaction in factors.

Table 5 ANOVA analysis

Term	*Coef*	*SE coef*	*T*	*P*
Constant	1,210.98	499.631	2.424	0.021
Grit size	–8.12	7.739	–1.049	0.302
Env. temp.	–10.01	8.535	–1.173	0.250
Speed	–0.48	0.386	–1.246	0.222
Hone ang.	–4.71	5.751	–0.820	0.419
Pressure	14.76	42.643	0.346	0.731
Time	–14.14	6.907	–2.048	0.049
Grit size * env. temp.	0.05	0.090	0.552	0.585
Grit size * speed	0.01	0.005	1.401	0.171
Grit size * hone ang.	0.04	0.074	0.565	0.576
Grit size * pressure	–0.25	0.569	–0.448	0.657
Grit size * time	0.17	0.095	1.840	0.075
Env. temp. * speed	0.01	0.004	1.517	0.139
Env. temp. * hone ang.	0.03	0.055	0.556	0.582
Env. temp. * pressure	0.19	0.435	0.448	0.657
Env. temp. * time	–0.02	0.072	–0.316	0.754
Speed * hone ang.	–0.00	0.003	–1.114	0.273
Speed * pressure	0.00	0.020	0.013	0.990
Speed * time	–0.00	0.003	–0.162	0.872
Hone ang. * pressure	0.10	0.299	0.326	0.747
Hone ang. * time	0.06	0.050	1.221	0.231
Pressure * time	0.18	0.413	0.433	0.668
S = 81.0992; PRESS = 633,107				
R-sq = 96.7%; R-sq (pred) = 96.5%; R-sq (adj) = 96.6%				

Table 5 ANOVA analysis (continued)

Analysis of variance for R_a						
Source	*DF*	*Seq SS*	*Adj SS*	*Adj MS*	*F*	*P*
Regression	21	423,124	423,124	20,148.8	3.06	0.002
Linear	6	314,556	54,783	9,130.5	1.39	0.249
Grit size	1	219,780	7,241	7,240.7	1.10	0.302
Env. temp.	1	2,463	9,044	9,044.3	1.38	0.250
Speed	1	17,140	10,203	10,203.2	1.55	0.222
Hone ang.	1	5,290	4,418	4,417.5	0.67	0.419
Pressure	1	53,694	788	788.4	0.12	0.731
Time	1	16,189	27,581	27,581.3	4.19	0.049
Interaction	15	108,568	108,568	7,237.9	1.10	0.394
Grit size * env. temp.	1	948	2,006	2,006.4	0.31	0.585
Grit size * speed	1	48,245	12,905	12,904.9	1.96	0.171
Grit size * hone ang.	1	5,851	2,103	2,103.2	0.32	0.576
Grit size * pressure	1	568	1,318	1,318.0	0.20	0.657
Grit size * time	1	19,180	22,274	22,273.9	3.39	0.075
Env. temp. * speed	1	11,036	15,130	15,130.4	2.30	0.139
Env. temp. * hone ang.	1	3,375	2,031	2,031.1	0.31	0.582
Env. temp. * pressure	1	1,133	1,319	1,319.1	0.20	0.657
Env. temp. * time	1	645	658	657.8	0.10	0.754
Speed * hone ang.	1	6,520	8,167	8,167.0	1.24	0.273
Speed * pressure	1	147	1	1.1	0.00	0.990
Speed * time	1	6	174	173.5	0.03	0.872
Hone ang. * pressure	1	285	697	697.0	0.11	0.747
Hone ang. * time	1	9,394	9,798	9,797.7	1.49	0.231
Pressure * time	1	1,234	1,234	1,233.8	0.19	0.668
Residual error	32	210,466	210,466	6,577.1		
Lack-of-fit	23	209,073	209,073	9,090.1	58.70	0.000
Pure error	9	1,394	1,394	154.8		
Total	53	633,591				

4 Results and discussion

It is evident that one value from each level of input parameters corresponding to the lowest possible square of errors has been selected. 3D scattered plot were plotted (Figures 10 to 15) between surface roughness vs. power consumption and input factors individually. Surface roughness of FG-260I cylinder liner using honing has been investigated by setting the individual optimum parameters. The best parametric combination has also been also optimised, i.e., grit size, environmental temperature, rpm, hone angle, fluid pressure and honing time is 43 µm, –5 deg., 1,200 rpm, 60°, 4 kg/cm^2 and 75 seconds respectively. The observed and predicted values of surface roughness have been analysed by performing the honing process using optimised parametric combination as R_a = 187.3 nm and R_a = 176.48640 nm consequently along with corresponding power consumption 1.3 Jule/second. It is very clear that RSM modelling technique is best fitted for the prediction of surface roughness and is able to successfully minimise R_a by 39.84% from its average value of R_a = 442.952 nm.

The honing processes were also performed on FG 260I using combined optimal parametric combination and average experimental surface roughness measured and given as Table 6.

Table 6 Optimisation of parameters

Material	*FG 260I*
Input parametric combinations: G_s, T_e, Vp, θ, P_f and M_t	43, –5, 1,200, 60, 4 and 75.
Predicted R_a (nm)	176.48640
Experimental R_a (nm)	187.3
Percentage error in R_a	6.126
Average R_a (nm)	442.952
Percentage optimisation of R_a (aver. R_a – pred. R_a)/aver. R_a ∗ 100	39.84%
Corresponding power cons. (W)	1.3

5 Conclusions

Honing process was done on grey cast iron (FG-260I) 100 cc motor bike cylinder liner using semi-automatic experimental setup. RSM is a robust design of experiment and modelling techniques which requires very less number of experiments to analyse the optimum surface roughness without altering any significant change in power consumption. RSM is the most powerful approach for modelling the honing process. It is also a fact that the most significant correlation coefficient (model 2 of FG-260I) was obtained between observed and predicted values of surface roughness. Present research has used the SRMSE approach as parametric optimisation to achieve the improvement of more than 39.4% from its average prediction in surface roughness under honing process.

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Nomenclature

HP	Honing of cylinder liner	T	Temperature
RSM	Response surface methodology	τ	Duty cycle
F	Feed	T_M	Machining time
V	Speed	R_a	Surface roughness
Gs	Grit size	MRR	Material removal rate
Gn	Grit number	MSE	Mean square error
Fn	Forces	AFM	Atomic force microscopy
Fp	Fluid pressure	Qe	Hone angle