Investigation of Surface Integrity of Cylinder Liner of IC Engine by Honing Process using RSM Technique

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Abstract

Honing is an important fine finishing operation, often used for internal cylindrical surfaces such as gun barrels, hydraulic cylinders, bearings and engine cylinder bores (Armergo and Brown, 1969). Excess material is removed by means of slow moving abrasive sticks pressed against the surface to be machined. Two kinds of motion, namely rotational and reciprocating are imparted by the honing machine to the hone (or honing tool) carrying the abrasive sticks. Although honing can be used on flat and external cylindrical surfaces too, it is predominantly used for finishing internal cylindrical surfaces (holes). Surface roughness of any manufactured components is an important and valuable performance measure, as far as theoretical and practical applications are concerned. It is widely used as an index of product quality and is in most cases a technical requirement for mechanical products (Ozcelik and Bayramouglu, 2005). Surface roughness is an important design consideration as it imparts many part characteristics such as fatigue strength, assembly tolerances, coefficient of friction, wear rate, corrosion resistance and aesthetics (Dabnun et al., 2005).There are implications of detailed topographical information scanned from cast iron automotive cylinder liners.. Worn and unworn surfaces measured both by AFM (Atomic Force Microscopy) and stylus .te Chauvin P.S. et al (2013) studied 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. cinques were compared visually and quantitatively using an effective relocation technique. Quantitative comparison was made of 3D and 2D surface parameters, such as root mean square roughness and slope which are significant for the tribological behaviour of the surfaces. The extra surface features found by the AFM measurements (e.g. steeper slopes and more peaks and valleys) significantly change the numerical values of the roughness parameters, and this scale-dependent difference, when compared with conventional stylus-measured parameters, points to the possibilities of deepening the understanding of cylinder liner lubrication in the light of more finely detailed measurements(Rosen et al.,1996).

Keywords: Honing Process, Surface roughness, RSM technique

Introduction

The numerical assessment of a surface texture is dependent on three types of characteristic lengths. These lengths are associated with the profile. Fig. 3.1 shows the different lengths of a sample surface.

Cut-off wavelength: This is the wavelength of a sinusoidal profile of which only a certain percentage of its amplitude is transmitted by the profile filter. It is the wavelength at which a filter becomes effective. For surface parameters, we normally analyses wavelengths between an upper and a lower cut-off: these are referred to as λs (shortest) and λc (longest). "Cut off" is also used synonymously as the sample length l_c. Filter is a process to exclude wavelengths above or below a particular frequency. The measurement system is a mechanical filter. Software can perform mathematical filtering. Profile filters are identified by their cut-off wavelength values.

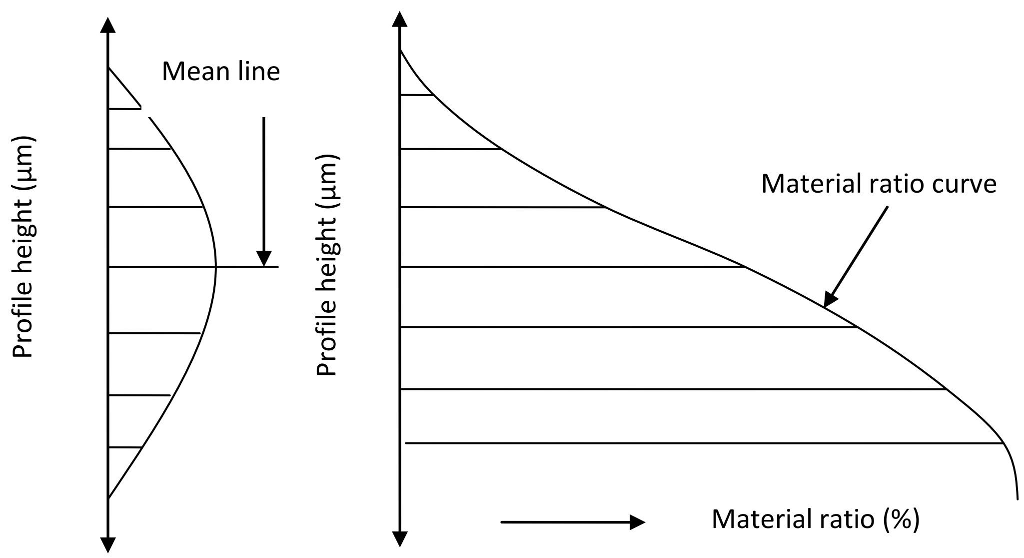
Sampling length: It is the length over which the parameter to be measured will have statistical significance, without being long enough to include irrelevant details. Generally, it is the longest spatial wavelength to be included in the profile measurement. Roughness sampling length (l_c) is the length within which the roughness average is measured.

Evaluation length: This is the length of the surface over which measurement is made. This length may include several sampling lengths. The selected length of the cut-off filter is normally at least 2.5 times the peak spacing, with two peaks and valleys within each cut-off. This cut-off would usually be 0.8 mm, but there are occasions when either a larger or a smaller cut-off length might be preferable for the surface under test. For primary profiles the evaluation length is equal to the sample length.

Traverse length: It is the total length of the surface traversed by the stylus in making a measurement. It is normally greater than evaluation length, due to the necessity of allowing run-up and over-travels at each end of the evaluation length to that any mechanical and electrical transients are excluded from the measurement.

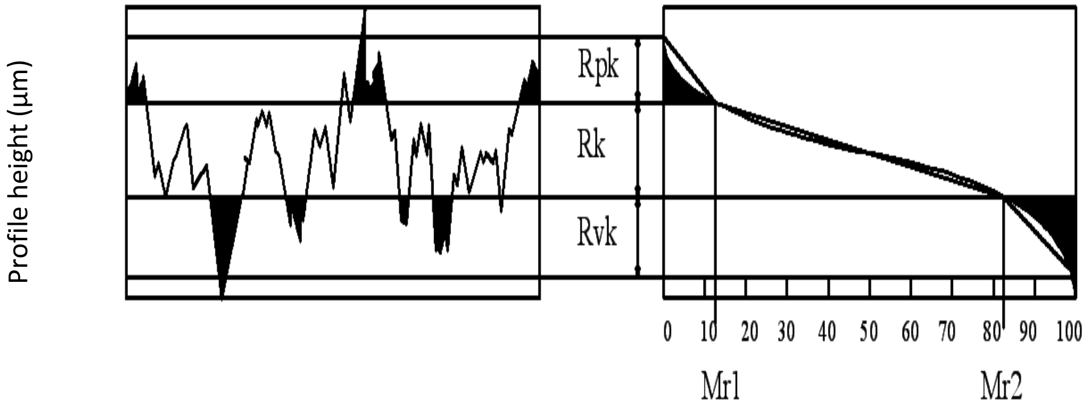
Surface roughness parameters

One of the most common uses of an engineering surface is to provide a bearing surface for another component moving past it. Their relative motion results in wear. The concept of bearing ratio, which simulates the effect of this wear, is widely used. The bearing ratio curve mathematically is the integral of the amplitude distribution function (ASME, 1996). Surface roughness parameters are based on an advanced statistical and bearing ratio analysis. Bearing (material ratio or Abbott) curves have been proposed to give a working representation of the portions of the surface at different depths. They combine aspects of contact area, contact mechanics and wear (Fig. 3.3). The DIN 4776 (1990) standard for honed bores used in the German automotive industry and currently standardized as ISO 13565-2 : 1996 provides a linear approximation of the bearing curve. The depth of profile below 40% bearing area is taken to indicate the steady state wear status of the engine (ISO 13565-2 : 1996).



(a) Amplitude distribution curve (b) Cumulative distribution curve

Linear material ratio curve (Abbott curve)



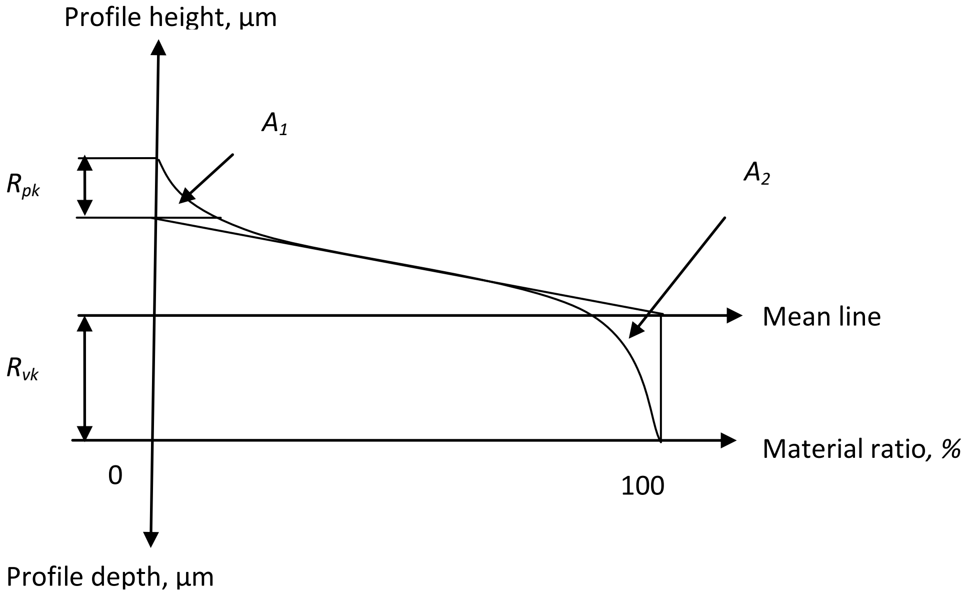
Sampling length (mm) → Material ratio (%) →

Hybrid parameters

The standard ISO 13565-2 specifies five parameters namely the reduced peak height R_{pk}, the reduced valley depth R_{vk}, the core roughness depth R_k, and material ratio determined by the straight line separating the core roughness from the material side M_{r1}, and that free from material sideM_{r2}(Fig. 3.4). This new standard suggests the use of R_k, R_{pk}, R_{vk}, M_{r1} and M_{r2} to replace R_a in the manufacturing of critical components like, cylinder bores, and connecting rods of an internal combustion engine (Jablonski and Pawls, 2001). In present investigation $R_a$parameter is being used so that the Atomic Force Microscopy can measure the center line average value at nanometer levels. The following definition of notation is presented on the basis of ISO 13565-2 (1996).

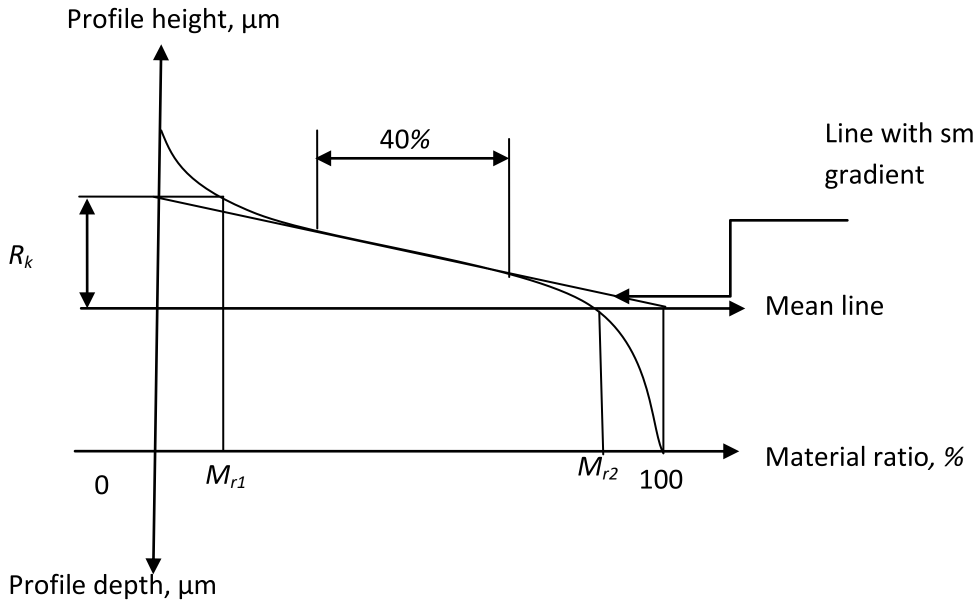
(i) Reduced peak height (R_{pk}): Normal calculations of material ratio are based on a defined reference level to avoid the influence of any extreme isolated peaks. These isolated peaks do not, however, affect the functional properties. Extreme isolated peaks and valleys are eliminated while calculating the peak height (R_{pk}) and valley depth (R_{vk}). The area of the peaks protruding above the core of the profile is represented on the material ratio curve by the surface A_1 (Fig. 3.5). This triangle is converted to a right angle triangle with the same area and the same length on the base line. The height of the triangle is the reduced peak height R_{pk}.Reduced peak height is erased by running in.

(ii) Reduced valley depth (R_{vk}): The area of the valleys below the core of the profile is represented on the material ratio curve by the surface A_2. This triangle is converted to a right angle triangle with the same area and the same length on the base line. The height of the triangle is the profile's reduced valley depth R_{vk}. It will retain lubricant in a functioning part.



Calculation of peak height (R_{pk}) and valley depth(R_{vk})

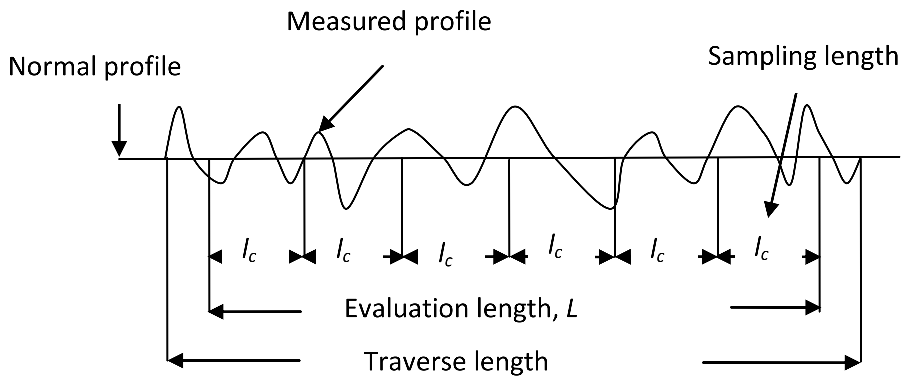
(iii) Core height (R_k): The material ratio curve, which represents the filtered roughness profile, is used to find the tangential line which has the smallest gradient and which has a length that includes 40% of all measured profile points.



Calculation of core height (R_k), material ratio $M_{r1}$and M_{r2}

The tangential line (Fig. 3.6) is extended so that it intersects the 0% and 100% abscissa on the graph of material ratio. The height of the resulting triangle constitutes the core depth of the surface profile and is designated as R_k. It is the difference between the heights of the slice levels at 0% of material ratio and at 100% of material ratio on this straight line. There is no real reason why the height intervals of this "arbitrary" construction should coincide with the peaks and valleys on a real honed surface. In fact, this arbitrary construction has been criticized by Zipin (1990) on the grounds that its connection to physical reality is rather (tenuous). Core roughness height determines the lifetime of the components. In actual measurement of this surface, the first step is to perform an ordinary triangle filter on the texture profile to get a first waviness profile. Next, this waviness is used as a truncation line: any primary profile, which projects below the waviness, is truncated to this waviness value. The truncated primary profile is next filtered with a second triangle filter. The result is R_k waviness. Subtracting from texture gives the R_k roughness.

(iv) Material ratio 1 (M_{r1}): At the points where the tangential line intersects the 0% and 100% abscissa, two lines are extended parallel with the material ratio axis until they intersect the material ratio curve. The point of intersection, which determines M_{r1}, shows the material ratio of the profile at the transition between peaks and core (Fig.3.6).
(v) Material ratio 2 (M_{r2}): The point of intersection, which determines M_{r2}, shows the material ratio of the profile at the transition between core and valleys.



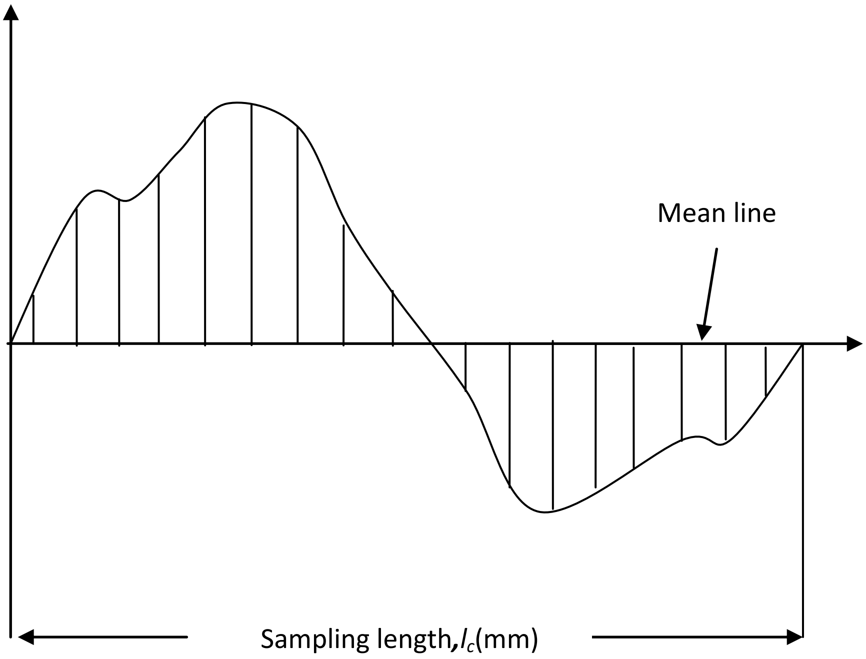
Traverse, evaluation and sampling lengths

(All dimensions are in mm)

3.2.2 Surface roughness parameters

Most engineering surfaces have approximately Gaussian height distributions. However, two texture characteristics are important from functional point of view. They relate to (a) smooth wear resistant and (b) load bearing plateau with intersecting deep valleys working as oil reservoirs and debris trap (Ogodorov, 2008). Typically, a honed component is machined first by rough honing and then by finish honing. It is possible to determine several roughness parameters like reduced peak height R_{pk}, reduced valley depth R_{vk}, the core roughness depth R_k, and material ratios determined by the straight line separating the core roughness from the material side (M_{r1}) and free from material side (M_{r2}) (Bohme, 1992).

Surface roughness is quantified by parameters which relate to certain characteristics of the texture. These parameters can be classified into three groups according to the type of characteristics that they measure. Amplitude measures the vertical displacements of the profile. Spacing measures the irregularity spacing along the surface, irrespective of the amplitude of these irregularities. Hybrid parameters measure both amplitude and spacing of the surface irregularities (Lavoie, 1992). Commonly used roughness parameters are described below. R_a(in micron/μm)is the most commonly used parameter in surface roughness analysis. It is also called Centre line average (CLA) or arithmetic average (AA). Mathematically, R_a is the arithmetic average value of the absolute departure of the profile from the reference line throughout the sampling length. The R_a value over one sampling length represents the average roughness such that the effect of non-typical peak or valley is averaged out and does not have a significant influence on the results (Feng and Wang, 2003). It does not give information regarding the shape of the irregularity. Fig. 3.2 shows a schematic diagram of the profile of a surface over the cut-off length.



Mathematical derivation of R_a and R_q

When evaluated from digital data, R_a is approximated by the trapezoidal rule:

$$R_a = (y_1 + y_2 + ... + y_n)/n$$

$$= \frac{1}{n} \Sigma y_i ;$$

where i varies from 1 to n. (Fig. 3.2)

R_a is calculated from the area between the roughness profile and its mean line, or the integral of the absolute value of the roughness profile height over the evaluation length.

$$R_a = \frac{1}{l_c} \int_0^{l_c} | y | \, dx ;$$

Similar surface profile shapes having different spacing may have different R_a. Similarly, if profiles differ in shape or spacing, it is hard to distinguish them by this measurement.

R_q is another method of calculating an average roughness value and is known as root mean square (rms). It is obtained by taking the square of each value of y and taking the square root of the mean of these values. It is more meaningful than R_a when used in statistical work (Feng et al., 2003).

Mathematically, R_q is given by the following equation.

$$R_q = \left(\frac{1}{n} \sum y_i{}^2 \right)^{\frac{1}{2}} ; \qquad (3.3)$$

where, i varies from 1 to n.

The root sum square (rms) average roughness of a surface may also be calculated from the following integral of the roughness profile.

$$R_q = \left(\frac{1}{l_c} \int_0^{l_c} y^2 \, dx \right)^{\frac{1}{2}} ;$$

There are several other amplitude parameters like R_t, R_z, and others. Spacing parameters measure the horizontal characteristics of the surface deviations. Spacing parameters used are peak count (P_c), mean spacing (R_{sm}) and high spot count (R_{hsc}) (Taylor Hobson, 2002).

Mechanics of honing process

Honing uses solid abrasives in the form of a set of blocks called hone, which remove the material from the work piece by a combination of shearing and ploughing action. The movement of hone produces a characteristic cross hatch lay pattern (Fig.3.7), which is conducive to oil retention. Due to low speed operation of the hone, the chances of surface damage by heat are minimized (Boothryod and Knight, 1989).

Kinematics of Honing: The hone is subjected to reciprocating and rotating motion. The cutting velocity (V_c) is the resultant of both reciprocating velocity (V_r) and rotating velocity (V_p) components. Crosshatch angle 2θ, (Fig. 3.7) is dependent on these two velocity components.

Let N be the number of revolutions of hone per second and D be the diameter of hole then, Rotational velocity = πDN

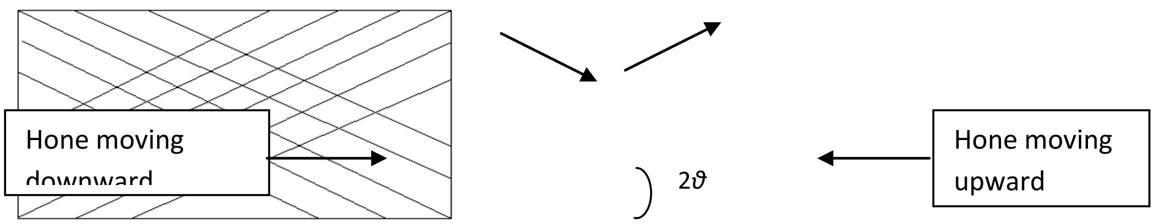
Let 'f' be the frequency of bore and L be the length of stroke,

Average linear velocity i.e. reciprocating velocity (V_r) = $2Lf$.

Resultant honing velocity, $$V_c = \left[V_p^{\,2} + Vr^2 \right]^{\frac{1}{2}} ; \qquad (3.5)$$

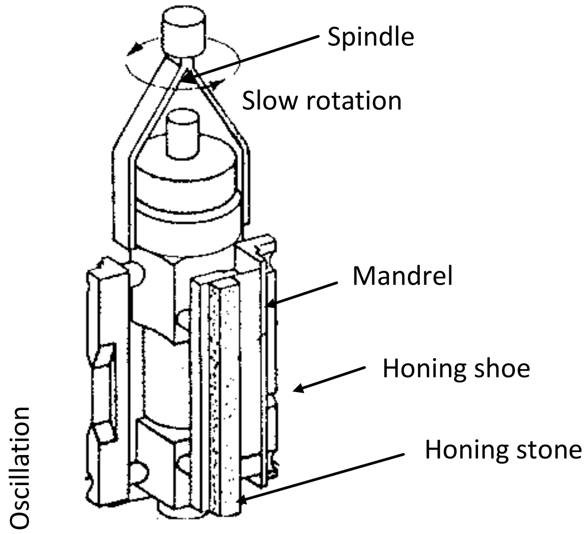
Let θ be the angle between the tangent of the path of grain motion at a given point and the plane perpendicular to the axis of rotary motion (Fig. 3.7). Cutting angle θ can be obtained by equation (3.6) in terms of the two velocities.

$$\tan \theta = \frac{V_r}{V_p} ; \qquad (3.6)$$



Crosshatch formation

In Fig.3.7 arrows on the crosshatch patterns show the directions of two perpendicular motions of the honing process. The surfaces of varying crosshatch angle are generated which affect the cycle average coefficient of friction. Friction decreases with decrease in crosshatch angle. The reduction of the crosshatch angle from 90º to 20º leads to 25% reduction in per cycle of coefficient of friction approximately (Michail and Barber 1995, and Jocsak 2005). Kumar et al. (2006) described a random base surface roughness profile generated by crosshatch. They defined the surface profile by specifying the probability distribution of the surface heights and the auto correlation function. Fig. 3.8 is the three dimensional view of a typical hone tool used for honing an internal cylindrical surface. Honing sticks are fixed in the hone head which is connected to the spindle that imparts a rotational motion to the spindle.



Typical honing head (Courtesy of DeGarmo et al., 1997)

Technological Selection of Parameters: Honing process parameters affect surface roughness in many ways. Some of the more important parameters that affect the honing process include: Rotational speed, speed of reciprocation, honing pressure, coolant temperature, grit size, honing time etc.

*Rotational Velocity (V_p)***:** Rotational velocity is considered as a technological parameter that affects the surface characteristics and material removal rate. Increase in peripheral speed decreases the surface roughness if other parameters are kept constant. Excessive speeds contribute to decreased dimensional accuracy, overheating of the work piece, and glazing of the abrasive. Overheating causes breakdown of the honing fluid and distortion of the work piece. The choice of optimum surface speed is influenced by the material being honed, hardness of the material, surface roughness required and number and width of the stones. Higher speed can be used for metals that shear easily, such as cast iron and some of the softer non-ferrous metals. Rotational speed varies normally between 20-35 m/min.

Reciprocation speed (V_r): Speed of reciprocation depends largely on the length of the honing tool and the depth of bore. It is the product of the number of stroke cycles per minute and twice the stroke length. Combination of reciprocation and rotational speed produces the typical crosshatch angle. When the rotation and reciprocation speeds are equal, the crosshatch angle is 90º. When rotation speed is greater than speed of reciprocation, the crosshatch angle is less than 90º. Reciprocation speed is less critical than rotation speed. Reciprocating speed varies between 12-25 m/min.

Honing fluid pressure: Honing is more often controlled by rate of feed-out than by gauge pressure. In general, higher feed rates are used for larger diameters, and lower feed rates are used for small diameters. Excessive pressure causes rougher finish because the abrasive is broken down too fast. Recommended values for contact pressure of honing tools made of different abrasive materials (Goetz&Burscheid, 1993) are given in Table 3.1.

Standard values for contact pressure

Abrasive material	Rough honing (N/cm^2)	Finish honing (N/cm^2)
Ceramic honing stones	50-250	20-100
Plastic bonded honing stones	200-400	40-250
Diamond honing edges	300-700	100-300
Boron nitride honing ledges	200-400	100-200

CHOICE OF SPECIMEN

The cylinder liner of an internal combustion engine of Motor bike is subjected to high rate cyclic loading. High accuracy and tight tolerances of piston in the liner of an automobile are ever more demanding requirements. Close tolerances and fits to mating components are specified for the sake of component reliability. The cylinder liner is manufactured by the powder metallurgy, forging and sometimes even casting. The powder forged (PF) liner is fabricated by consolidating metal powders into a form, sintering the form and machining to final dimensions. The forged cylinder liner is fabricated by starting with a wrought steel billet, followed by forging and machining to the required dimensions. The quality of the bore surface of a components influences oil consumption, noxious emissions and running performance. Inner surfaces of the cylinder liner are finished by rough honing followed by finish honing. In the present investigation, the honing experiments were conducted on cylinder liner used in the 110 cc Honda motorbike cylinder liner. Three different grades of grey cast iron cylinder liners were used as the work piece for the honing operation. The chemical compositions of materials of the cylinder liners are given in Table 4.1, 4.2 & 4.3.Work piece materials were normalized and shot blasted. Pearlite and ferrite structures were more or less uniformly distributed in the materials. The hardness of the materials were measured as 250 BHN, 230 BHN and 166 BHN respectively for three different grades of grey cast iron EN-GJL 250, FG 260I and HT 100 respectively. Fig. 4.1 shows the geometric details and dimensional tolerances of chosen cylinder liners.

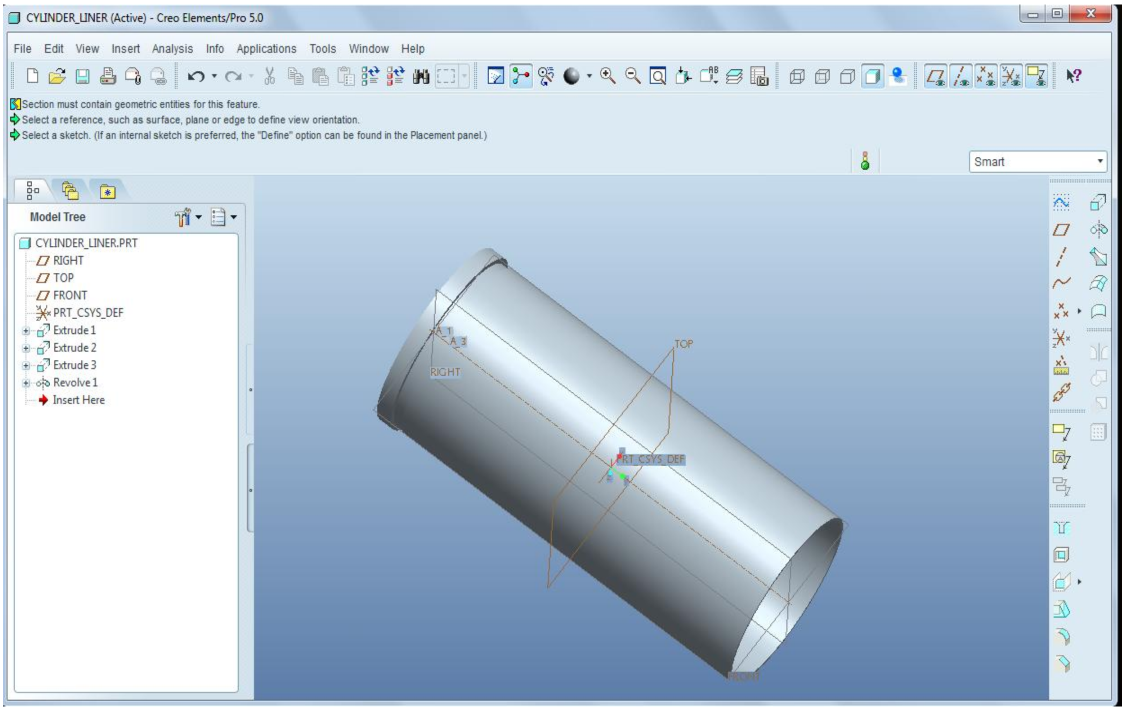


Fig. 4.1: Geometry of cylinder liners (All dimensions are in mm)

Chemical Composition of Gray Cast iron Hardness - 250 BHN

C	Mn	Cr	Ni	Mo	S	P	Si
2.80	0.61	0.35	0.04	0.08	0.02	0.02	2.21

SURFACE ROUGHNESS TESTER (AFM)

Atomic Force Microscope(Fig. 4.5) is suitable equipment for measuring surface roughness parameters. It is only equipment which can measure R_a values very closely; other equipment have are comparatively poor levels of accuracy or flexibility.

Table 4.7: Specification of AFM

Primary Analysis	Filter: Gaussian Cut offs (l_c) None, 0.0025 mm- 0.8 mm
	Parameters: P_a, P_q, P_v, P_t, P_{sk}, P_p, P_{ku}, P_z, PL_{amq},
Roughness Analysis	Filter: Gaussian, ISO 2CR, 2CR PC Cut offs (l_c) 0.08 mm – 8.0 mm Bandwidths: 30:1, 100:1, 300:1
	Parameters: R_a, R_q, R_p, R_v, R_t, R_{sk}, R_{ku}, R_z, R_z, R_{z1max}, R_{3y}, R_{3z}, RS, RS_m, RL_o, R_c, RD_{ela}, RL_{amq},
R_k Analysis	Filter: Gaussian Cut offs (l_c) 0.08 mm – 8.0 mm Bandwidths: 30:1, 100:1, 300:1
	Parameters: R_k, R_{pk}, R_{vk}, M_{r1}, M_{r2}

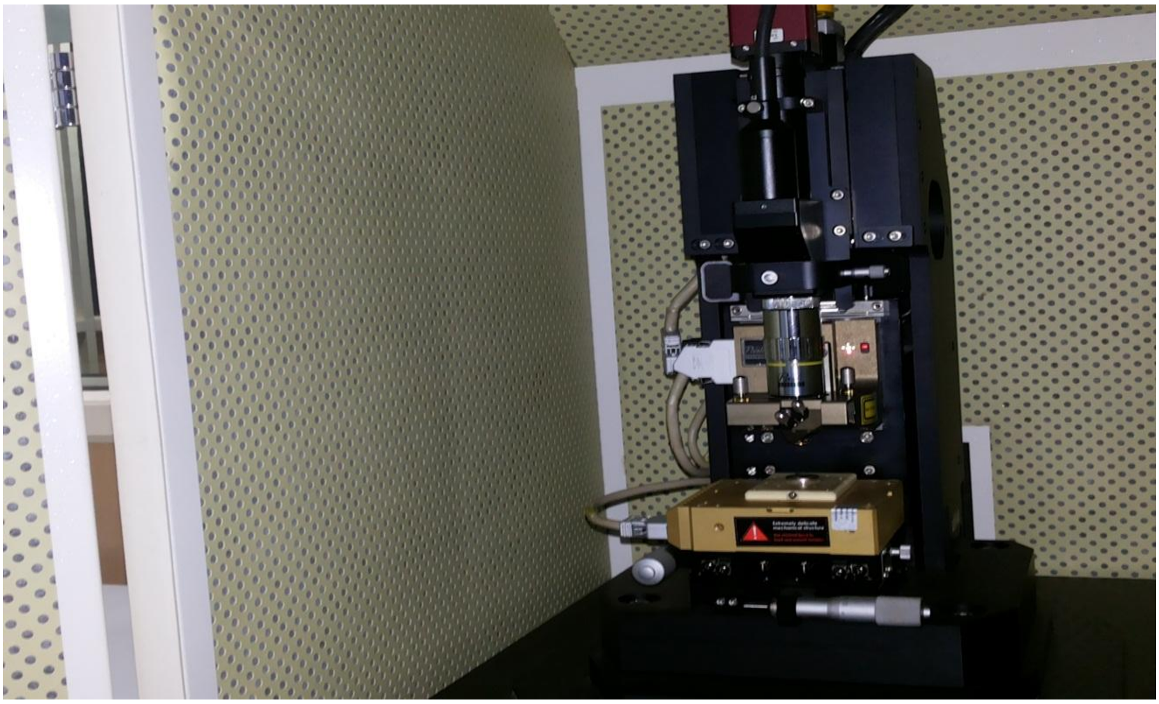


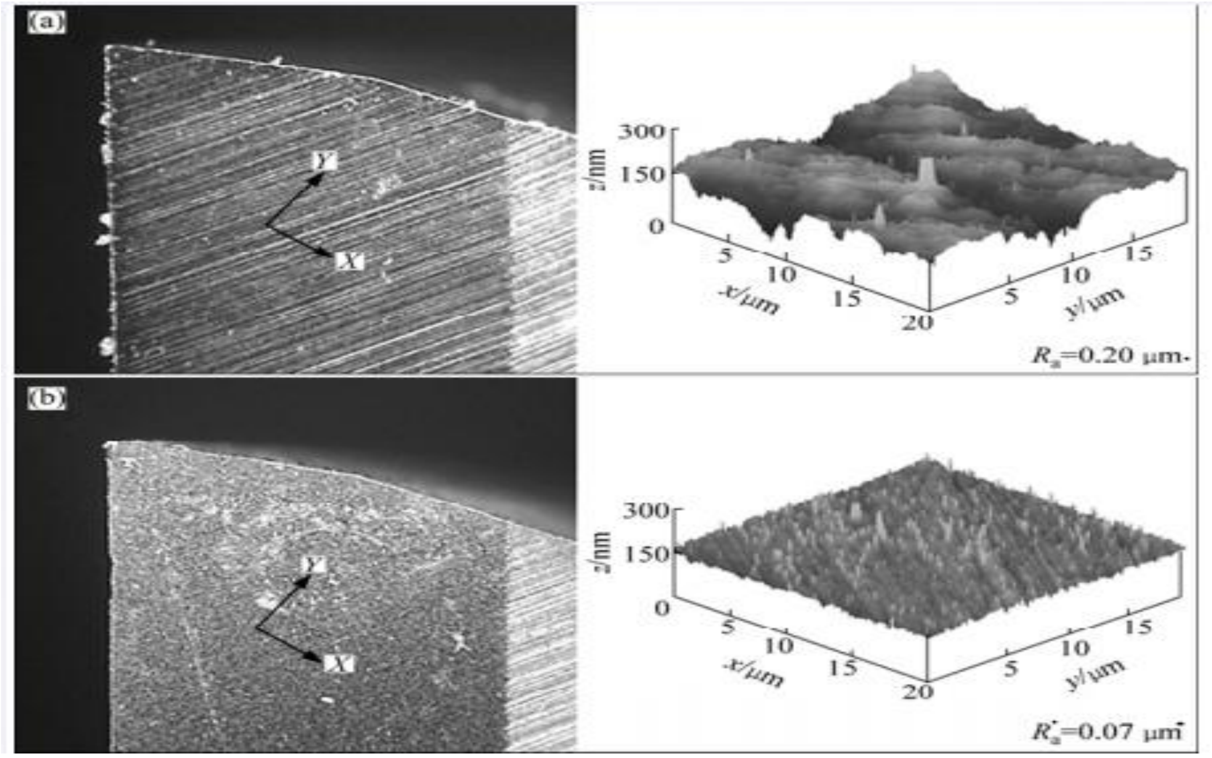
Fig. 4.5: Atomic Force Microscope (AFM Laboratories)

Measurements can have an extremely high resolution compared to stylus profilometers or white light interferometers, often even higher than the scanning electron microscope (SEM). In several studies AFM measurements of a surface are considered the benchmark. Although the lateral resolution is much higher than above-mentioned techniques, the range both laterally and vertically is limited (108x108 μm and 6 μm respectively with the equipment available). Care must be taken when conducting AFM measurements as external vibrations can have a severe impact on the measurements, as can improper engagement of the tip onto the sample.Olsson et al. compared the three techniques, SP, WLI and AFM,by measuring a range of engineering surfaces, a cylinder liner, steel roller, gear surface and steel sheet. With the AFM measurements as a benchmark calculation of roughness parameters, including the R_a set, showed a variation of between 5-20%.

Poon and Bhushan et al.(1995) conducted a similar study. They investigated the Rq, Rp and Peak to Valley (P-V) parameters and found that the calculated results were ordered as WLI<SP<AFM, while the inverse was true for the correlation length. Processor control module (PCM) provides an operator interface and data processing capability for the instrument. All instrument commands, analysis requirements and results displays are via a touch pad screen. Instructions and data are passed between the processor control module and a compatible traverse unit via an interconnecting lead or an infrared link. This enables the processor control module to be used up to a distance of 1.0 m from the traverse unit.

Topographical Representation of Cylinder Liner in Honing:

Fig. shows the CCD images and AFM images of Gray Cast iron(HT100). The AFM images indicate that the surface morphology of cylinder liner material considerably depends on honing operation. The average surface roughness (RMS) of experimental material was calculated from AFM images of selected areas of 3 μm×3 μm. The surface morphology of the HT100 material with no honing operation (Fig.4.6 a) was found to be rough (RMS, 0.20 μm). In the case of honing operation (Fig.4.6 b), HT100 material had a greatly smooth surface morphology (RMS, 0.07 μm), which was due to the roughness improvement of the material inner surface. Parallel corresponding Fig shows the curves of surface roughness of cutting tool versus honing time. The honing curves showed a rapid improvement initially and thereafter the surface roughness became steady at honing time of 20 s, manifesting a saturation effect.The optimal honing time under given honing conditions was determined to be approximately 20 s with respect to surface roughness.



Topography of gray cast iron a) Before honing process b) After honing process

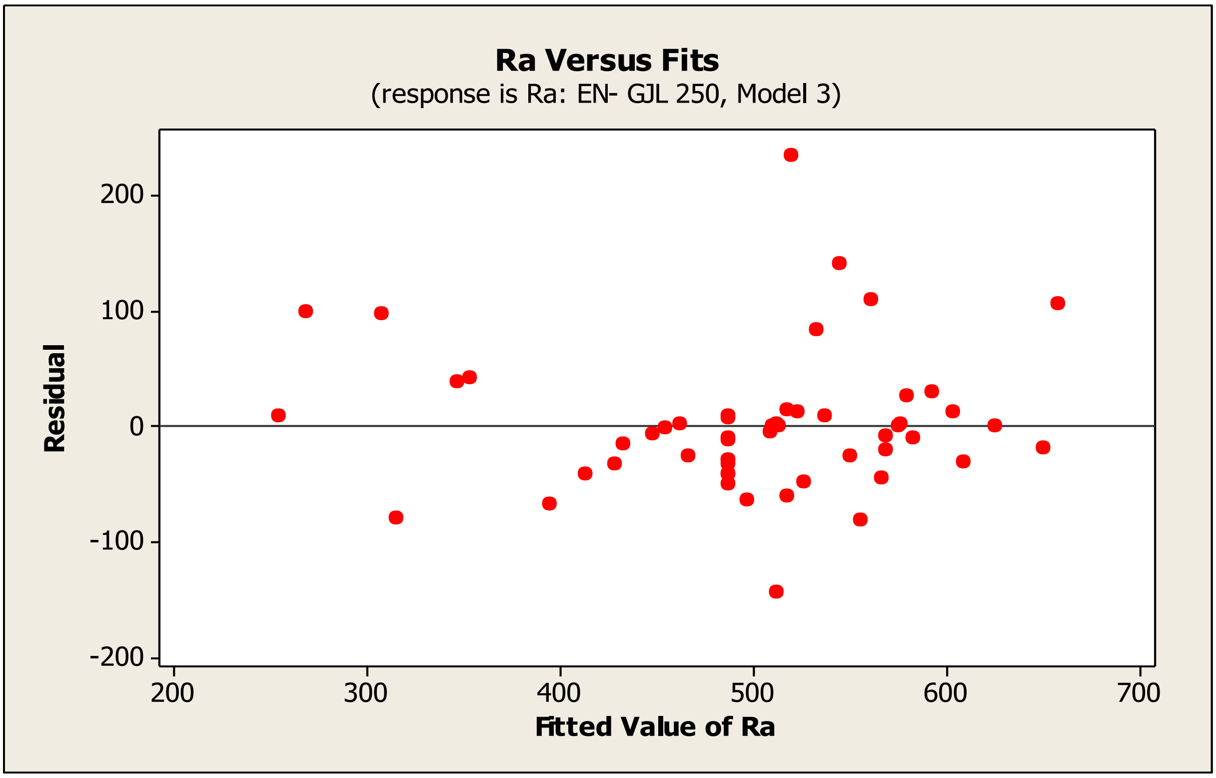
Sl. Nos.	Grit Size (μm)	Environmental Temp. (°C)	Rotational Speed (RPM)	Hone Angle (Deg.)	Fluid Pressure (Bar)	Honing Time (Sec.)	R_a (nm)	Power (Kw)	Micro Hardness (HV1)
1	43	40	600	60	9	60	440	2.3	190
2	68	10	600	20	4	60	575	4.1	188
3	68	10	600	20	9	30	625	4.1	191
4	43	10	1200	60	4	30	366	2.0	195
5	68	10	600	60	4	30	524	3.4	201
6	43	10	600	20	4	30	578	2.2	205
7	43	40	1200	20	4	30	417	2.7	210
8	56	25	900	40	6.5	45	458	3.6	221
9	56	25	900	40	6.5	45	436	3.6	214
10	56	25	900	40	6.5	45	495	3.5	192
11	68	40	600	60	4	60	617	4.4	205
12	68	10	1200	20	4	30	560	3.5	208
13	68	10	1200	60	9	30	509	3.7	231
14	68	10	1200	20	9	60	616	4.3	222
15	43	40	1200	20	9	60	384	2.7	196
16	68	40	600	20	4	30	478	3.8	199
17	68	40	1200	60	9	60	631	4.8	225
18	43	10	1200	60	9	60	405	3.1	216

19	68	10	1200	60	4	60	512	3.3	200
20	56	25	900	40	6.5	45	445	2.8	194

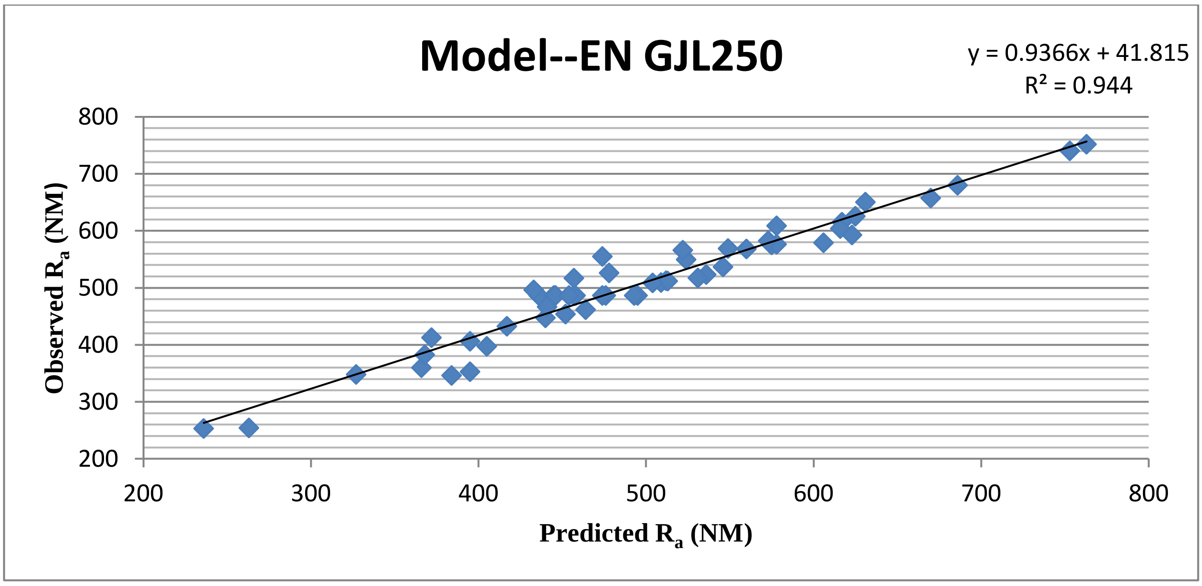
Prediction spreadsheet with corresponding power consumptions

and Micro Hardness in EN-GJL 250

Sl. Nos.	Model				
	R_a(Obs)	R_a (Pred.)	HV1 (Obs.)	HV1 (Pred.)	Power (KWh)
1	440	447.44809	190	186.194	2.3
2	575	575.406515	188	189.393	4.1
3	625	625.656515	191	191.115	4.1
4	366	360.024156	195	195.817	2.0
5	524	549.654397	201	205.607	3.4
6	578	576.478701	205	206.214	2.2
7	417	432.707352	210	209.735	2.7
8	458	486.672451	221	221.781	3.6
9	436	486.672451	214	211.781	3.6
10	495	486.672451	192	191.781	3.5
11	617	615.252734	205	202.271	4.4
12	560	568.259263	208	201.571	3.5
13	509	509.406515	231	236.296	3.7
14	616	604.031135	222	223.443	4.3
15	384	346.376738	196	201.037	2.7
16	478	526.239339	199	199.691	3.8
17	631	650.41645	225	219.957	4.8
18	405	397.492267	216	206.911	3.1
19	512	512.656515	200	206.232	3.3
20	445	486.672451	194	200.097	2.8



R_a versus Fits plots have been drawn for the material and also the correlation coefficient plot between the RSM predicted and observed surface roughness plotted as in Fig, to predict the best model.



shows the graphical representation of $R_a$versus Fits which indicates the goodness between observed and predicted responses. TheR^2 values and the slope ofpredictions of $R_{a(}$surface roughness) has been represented by Fig The correlation coefficients of the model is 0.944 . It shows a good relationship between the two values. Its gradient is 0.9366 which is also close to unity

Literature Survey

A brief review of the published studies on the use of techniques based upon regression analysis and RSM for analysis of various machining processes is presented. The survey reveals marked trend in the use of the regression analysis and RSM techniques in the construction of models for the analysis of manufacturing processes and optimization of process parameters. Literature survey shows that a lot of work has been done on modelling of machining processes like, turning, milling, drilling and grinding in the context of surface finish using response surface methodology. Various researchers, however, have taken different parameters for study the surface roughness using RSM modelling. No work has been reported on surface roughness modelling and optimization using RSM modelling in honing process applied to fine finishing of the bore of grey cast iron made cylinder liner with six affecting parameters. Conclusions from the literature review have been included

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