4.0. VARIABILITY FACTORS IN MACHINED SURFACE ROUGHNESS

4.1 INTRODUCTION:

The surface finish is affected by many factors. Some are controllable such as cutting speed, feed, depth of cut and tool geometry (mainly nose radius and the two cutting edge angles). Others are uncontrollable or inherent such as grain size, noise of gear boxes, randomness in variations of work-tool metallurgical/physical/mechanical properties causing minute random variations in forces. There are the third variety of factors which can only be identified as harmful and parasitic effect such as tool wear status, side flow, groove wear and built up edge etc.

Though several authors have dealt with almost all the factors, but all of them failed to draw a clear picture - a quantitative holistic one, as they dealt each factor as individual.

Let us make a clear distinction between a surface finish generated (or ideal) and the surface finish obtained (or the actual). When a finish is generated under certain controllable parameters and therefore predictable and deterministic, there seems to be some mechanism (those uncontrollable and parasitic factors which are stochastic in nature) operating either to improve or to deteriorate the already generated surface before we get it.
As already pointed out in Chapter 3.0.9, the $R_{\text{max}}/R_a$ ratio can serve as a good indicator to identify the factors responsible to improve or to deteriorate the ideal surface finish in terms of $R_a$. It is found that ideal value of $R_{\text{max}}/R_a$ should be around 4 and when the random variations are superimposed the $R_{\text{max}}/R_a$ should be around 5.28. Therefore, taking into effect the controllable and uncontrollable factors the value of $R_{\text{max}}/R_a$ should normally be around 3 to 6.

But the experimental values of $R_{\text{max}}/R_a$ varies widely between 0.5 to 15. Therefore, it can be concluded that depending on feed, at low feed level there are factors that cause worsening of the surface and reduce the ratio $R_{\text{max}}/R_a$ below 3 and at moderately high feed there are factors which cause improvement in the surface causing the $R_{\text{max}}/R_a$ ratio to attain a value higher than 6.

The variability can be explained thus:

(a) There is a random factor determined by the noise of the machine (gear boxes) under a given set up, surface finish of the tool flank in contact with the finished surface, plus the property variations of the work-tool pair. This is inherent and uncontrollable factor, determines the "minimum limit of the attainable surface finish". This is something like process capability with respect to tolerance. This minimum limit can be
found by extending the $R_a$ Vs feed, 3 line to zero-feed. This should be called "process capability with respect to surface finish". This is applicable to only very good finishing operations at very low feed values.

(b) Over and above this, there are certain mechanism operating either to deteriorate or to improve the already generated surface finish. "Side flow" is the cause of the deterioration, more appreciable at fine finish i.e. with low feed turning where $R_{\text{max}}/R_a$ ratio is less than 4. Since the value of $R_a$ due to side flow is very small say less than one micron, this variation will be significant only at fine turning. Further, the side flow will depend on the hardness of the material. It is obvious that more soft material will flow more than a harder material. The side flow will also depend on the tool geometry. The tool geometry which will cause the chip to flow towards auxiliary cutting edge is likely to cause side flow and resultant variation in roughness. Therefore, high value of principal cutting edge angle ($\phi$), a positive high value of inclination angle ($\lambda$) and low value of auxiliary cutting edge angle ($\phi_4$) may be detrimental to the production of a good surface finish due to side flow.

(c) On the other hand, when turning with a moderate feed rate we observe $R_{\text{max}}/R_a$ ratio greater than 6, meaning an improvement in the value of $R_a$ (lower than expected). This improvement in
surface finish is caused by what can be named as "Burnishing effect". More nose radius, more speeds, more radial pressure and less nose friction are some of the conditions favourable for "Burnishing effect" causing better finish.

(d) The grain size and the strength of the materials are closely related by Hall-Petch equation. Even the distribution pattern of grain size in metal can alter the strength, hardness and ductility character of metals. The grain size and hardness variations and the accompanied surface roughness variations are correlated and discussed in Chapter 5.0 separately.

(e) It is necessary to keep the built up edge formation and the chatter out of consideration as these are not proper cutting conditions suitable for fine turning.

(f) Classification of parameters having influence on surface finish:

1. Parameters of materials physical characteristics.
   A. Materials inner defect
      Various kinds of pores
   B. Materials brittleness
      Ploughing, cracking, influenced by the sharpness of cutting edge.
C. Materials ductility

(i) Finished surface deformation caused by burning phenomenon on finished side.

(ii) Retouch of chips on finished surface on occasion of chip generation.

(iii) Generation of machining transformed layer on finished side.

D. Materials finishability depending on the machinability and composition of work material, grain size, hardness etc.

2. Parameters of materials chemical characteristics.

A. Built up edge

(1) Adhesion of taken off splinter

(2) Change of over cut volume

B. Adhesion

Touch between adhered material on front cutting edge and finished surface. This touch is related to cutting pressure, cutting temperature and deformability of material.

3. Geometric parameters.

.. Tool geometry

(1) Nose radius

(2) Principal/front cutting edge angle.
(iii) Auxiliary/side cutting edge angle
(iv) Inclination angle— to determine the chip flow direction.
(v) Tool shape change due to defect or wear
(vi) Wear status mainly flank and groove wear.
(vii) Rake angle – for side flow.

B. Cutting condition

(i) Cutting feed rate
(ii) Cutting speed
(iii) Depth of cut

4. Other parameters depending on work-tool-Machine system

A. Trembling vibration or noise due to gear box and bearing rotation and also depending on the rigidity phenomenon of work-tool-Machine system.

B. Friction condition – use of cutting fluid depending on work-tool pair.

C. Temperature – use of higher speed, controlled by cutting fluid (coolant).

D. Machinability – Tool life – wear phenomenon already mentioned.

5. Random factors and others:

A. Surface finish of the tool flank surface in contact with finished surface.
B. Random variation in composition and hardness of work materials.

C. Force factors - the magnitude, variation in various component of forces specially the thrust force.

D. Retouches of chips and finished surface when chip pocket is filled with chip in case of brittle material like Cr or chip adheres on finished surface (burring).

E. Depositing flakes of chips on finished surface (flagging, flaking).

F. (i) Sponzipfil
   (ii) Side flow
   (iii) Built up edge.

4.2. THE EFFECT OF MICRO CHATTER (NOISE)

As it has been already pointed out, at the lowest level of feed for very fine finish the effect of micro-chatter, sponzipfil, side flow combined with built up edge deteriorate the surface finish. As a result the roughness is much higher than expected as given by the ratio $\frac{R_{\text{max}}}{R_{a}} \leq 4$.

The micro-chatter can be taken care of by superimposing the chatter function, which is also periodic but random in nature, on the regular geometric and periodic function of the ideal surface roughness obtainable on the basis of feed and tool shape at the tip.
Mathematically, if the theoretical surface roughness function can be represented as

\[ R_1 = f_1(s, r, \phi, V, d) = f_1(X)_1 \]

and the micro chatter and the random function as

\[ R_2 = f_2(s, r, \phi, V, d) = f_2(X)_2 \]

Then the net effect is

\[ R = R_1 + R_2 = f_1(X)_1 + f_2(X)_2 = f(X). \]

To do that we must represent the functions in suitable series form like Fourier's.

4.3. SIDE FLOW:

The flow of metal perpendicular to the direction of cutting (side flow) is the single dominant factor causing the surface finish decrease at the low feed, low speed cutting. The quantitative determination of side flow during actual cutting test is very difficult. But its existence is nevertheless proved with the help of scratch test by various authors. Further it is observed during turning of ductile materials with a tool having large principal cutting edge angle, in the form of ring formation. Though the side flow towards left (to uncut surface) is of no consequence, the side flow towards right (to the corners where the auxiliary cutting edge is in contact with just finished surface) actually deposits additional metal on to geometrical crest form thereby
increasing the so called peak to valley height, so that $R_{\text{actual}} > R_{\text{th}}$ as shown in Fig. 4.1. The amount of deviation is low, therefore, it is appreciable only when the crest is also low or in other words for very fine finish turning with very low feed value. At low speed cutting, and also when the rake angle is low or negative, the stagnant phenomenon causing built up edge may increase the side flow. Therefore, built up edge not only directly effects the surface finish but also indirectly increases the side flow and cause the deterioration in surface finish. The side flow should also increase due to increase in nose radius, but the effect on the surface roughness due to such is not appreciable as the geometric effect of nose radius and feed on the surface roughness reduction is in comparison much more.

The other very important factor which is responsible for the side flow is the material factor itself. Definitely, the hardness and ductility will matter much. In scratch test with V-tool, on various metals and at various speeds, it was observed that the side flow increases when the angle of Vee increases, speed decreases and the metal is softer. It is further observed that the side flow height can be as much as the depth of the scratch. In fine turning therefore, an amount of side flow which can increase the roughness ($R_{\text{max}}$) from 2 $\mu m$ to 4 or 6 $\mu m$ is very much appreciable but the same amount of side flow increasing roughness ($R_{\text{max}}$) from 12 $\mu m$ to 14 or 16 micron is not very significant in proportionate figure.
The amount of side flow may be expressed as ratio of \( \frac{a}{A} \) and \( \frac{h}{t} \) as shown in Fig. 4.2. The effect of rake angle and cutting speed on side flow and on surface roughness as observed by Selvam and Radhakrishnan are reproduced in Figs. 4.3 and 4.4.

Over and above this if the effect of built up edge is considered then further deterioration in surface roughness can be explained. However, the built up edge can cause deterioration in finish even at semi-finish operation at moderate feeds directly by leaving a part of it on the finished surface and also by alternation of the tool geometry from its best performance.

Therefore, it can be concluded that at low feed when \( \frac{R_{\text{max}}}{R_a} \) ratio is found to be less than 4, indicating an increase in surface roughness from its ideal, the cause may be due to side flow. The factors which can cause side flow are also listed namely:

(a) Tool geometry mainly, the principal cutting edge angle \( \phi \), auxiliary cutting edge angle \( \phi_1 \) and Nose radius \( r \). Side flow will increase if \( \phi \) and \( r \) are more.

(b) Rake angle; side flow increases as the rake angle is decreased.

(c) Cutting speed, side flow increases as the speed is decreased.

(d) Material factor; side flow will be more for a softer material.
(e) Built up edge: Side flow will be more with the conditions that favour formation of built up edge.

It is further concluded that side flow is the most important factor to explain the variability at the fine finish turning at very low feed(S), and it increases the roughness from its ideal or theoretical value. Though side flow will be there at high feed cutting too, but its effect will be marginal.

At moderate to high feed cutting the surface finish is really better than the theoretically expected value as indicated by: \( \frac{R_{\text{max}}}{R_a} > 4 \). Such an improvement can be explained by mechanisms other than side flow.

A combined factor which can be appropriately named "Burnishing" effect, may explain such variability very satisfactorily.

4.4 BURNISHING EFFECT

As it has been pointed out in Chapter-3, when \( \frac{R_{\text{max}}}{R_a} \) ratio is greater than 4, that indicates the value of \( R_a \) must be less than the theoretical value, thereby increasing the ratio \( \frac{R_{\text{max}}}{R_a} \). Which means that at this level of feed, there is an appreciable decrease in roughness value or we get a better than expected surface finish.

It is therefore necessary to identify the factors responsible for the improvement in surface finish. The action of these factors can be easily explained and understood.
altogether instead of each individual. The combined effect thus found can be named "Burnishing Effect" as it is similar to common burnishing. It is necessary to identify the cause of burnishing. Four things are very important— the softness, radial pressure, the relative speed and nose friction. Those conditions by which the radial pressure (force $P_y$) increases and interface flank friction reduces, a better surface finish is obtained due to burnishing. Speed can directly effect burnishing and also indirectly help burnishing by friction reduction. The higher values of nose radius or lesser values of $\phi$ and $\phi_1$ increases the value of radial force, $P_y$ thereby inducing burnishing. Therefore, at higher nose radius the surface finish is not only better as found geometrically, it is further improved by burnishing. Therefore, the observed improvement in surface finish at higher speed may also be explained by burnishing effect. The surface finish improvement while cutting with a cutting fluid can also be explained due to friction reduction. Friction is also less at higher speeds.

If material factors is considered, the softer material will induce more burnishing effect and will give a better surface finish. However, softness and tool nose radius are also responsible for side flow causing higher roughness. By burnishing, the crests are flattened to smoothen the surface to a reduced value of Peak to Valley height. Consequently, the value of $R_a$ will be also less as shown in Fig.4.5.
Burnishing is also affected by cutting speeds. Therefore, it is well understood why a reduction in surface roughness is observed at higher cutting speed.

The effect of flank wear will be very interesting. A little flank wear will be helpful to improve finish by burnishing, but as the flank wear grows, a limit will be exceeded when the surface finish will begin to deteriorate. The initial improvement is due to ironing but as the worn surface is of lesser finish due to scratch marks, it is likely to worsen the surface after a certain limit of flank wear is exceeded. This effect of flank wear will be valid only for higher level of feed. For very fine finish feed, even a little flank wear will be harmful.

4.4.1 The Radial Force (Py)

When there is no built up edge the cutting tool is in contact with the machined surface on the flank side under the radial force \( (P_y) \) and a friction force \( F' \).

The total radial force on the nose \( P_y \) is the sum total of the \( P_y \) component of the tool force and the Normal force \( N' \) (due to friction and elastic).

To determine the normal force, \( N' \), the contact of the nose flank with the material machined can be considered elastic since
plasticity condition is fulfilled only at the cutting edge where the contact stresses reach a maximum.

The contact conditions can be looked upon as a case of indentation of a long narrow stamping die with rounded edges, beneath which the material machined goes into a plastic state. This facilitates the smoothening of the ridges (crests) to a lower level resulting in the decrease of roughness height.

Using the solution of an analogous problem by Zhtayerman, and taking into consideration of the influence of the friction coefficient on the contact stresses from Saverin's formulae, Zorev (131) derived the following relationship for the normal force, \( N' \), on the nose flank contact surface of the tool:

\[
N' = \frac{\pi b L T_s (\pi - 2 \beta_0 - \sin 2 \beta_0)}{\left(0.5 + 2\mu^2\right) \left[ \sin \beta_m \ln \left| \frac{\sin(\beta_m + \beta_0)}{\sin(\beta_m - \beta_0)} \right| + \sin \beta_o \ln \left| \tan \frac{\beta_m + \beta_0}{2} \right| \right]}
\]

where

- \( T_s \) = the shear stress on the surface layer of the material being machined;
- \( b \) = the length of the contact of the clearance surface with the material machined (width of cut).
$L$ = the half-width of the contact of the clearance surface with the material machined or what is half width of the clearance surface wear face;

$\mu^*$ = the coefficient of friction of the clearance with the material machined.

$\beta_m, \beta_0$ are certain additional parameters which are determined from the solution of the system of equations given below:

$$\ln \frac{\sin (\beta_m + \beta_0)}{\sin (\beta_m - \beta_0)} = \tan \beta_m (\pi - 2\beta_0)$$

Putting

$$\ln \left| \frac{\tan \frac{\beta_m + \beta_0}{2} - \tan \frac{\beta_m - \beta_0}{2}} \right| = (Y)$$

and

$$\ln \left| \frac{\sin (\beta_m + \beta_0)}{\sin (\beta_m - \beta_0)} \right| = (X)$$

Also

$$\frac{BL (0.25 + \mu^*^2)}{1 - v_1^2 + 1 - v_2^2} = \frac{2 \pi \tau_s}{\sin \beta_m (X) + \sin \beta_0 (Y) + (\pi - 2\beta_0) \cos \beta_m}$$

where

$E_1$ and $v_1$ are the elastic constants of the material machined

$E_2$ and $v_2$ are the elastic constants of the tool material

$B$ is the curvature of the edges of the wear face of the rear surface (reciprocal of nose radius).
The above relationship show that the normal force on the nose flank, $N'$ depends on nine factors. Amongst these factors the elastic constants $E_1$ and $E_2$ and Poisson ratio $\nu_1$ and $\nu_2$ vary within a very narrow limit even less than 10%. There are only five factors which can have a significant influence on the forces acting on the clearance surface namely, $\tau_s$, $b$, $L$, $B$ and $\mu'$. 

The influence of the width of cut $b$ on the force $N'$ is obvious. According to relation it is characterised by a direct proportional connection. The influence of other four factors is not so obvious since they enter into the system of equations and influence force $N'$ through parameters $\beta_m$ and $\beta_0$. To discover the influence of these factors by means of the above relations, the curves were drawn for partial relationships of the normal force $N'$ to $\tau_s$, $L$, $B$ and $\mu'$, as shown in Fig. 4.6. The curves are drawn by varying one factor and keeping other factor constant: $\tau_s = 46 \text{ kg/mm}^2$; $L = 0.07 \text{ mm}$; $B = 5 \text{ mm}^{-1}$; $\mu' = 0.36$; $b = 10 \text{ mm}$; $\nu_1 = \nu_2 = 0.3$; $E_1 = E_2 = 2.1 \times 10^4 \text{ kg/mm}^2$.

According to curve 1 the normal force $N'$ grows rapidly as the shear stress of the material machined ($\tau_s$) increases. This occurs because the plasticity condition in the neighbourhood of the cutting edge can be fulfilled as the shear stress rises if the normal stress and the force $N'$ on the contact surface increase accordingly.
Curve 2 shows that force $N'$ grows considerably as the half-width of the wear face $L$ increases. The greater the width of the wear face, the greater the area over which the normal contact stresses act and the greater must be the sum of these forces - the force $N'$.

According to curve 3, the normal force on the clearance surface drops as the curvature of the edges of the wear face $B$ grows (nose radius decreases). This happens because as the curvature $B$ grows the stress peaks on the edges of the wear face increase, and the zone of activity of these peaks the plasticity condition is satisfied at a smaller value of force $N'$.

According to curve 4, the normal force on the clearance surface drops as the friction coefficient increases. The physical meaning of the relationship obtained is that the tangential stresses on the contact surface grow as the friction coefficient increases. For the plasticity condition to be fulfilled at elevated tangential stresses smaller normal stresses, and thus also a smaller force $N'$, must be applied.

Knowing the influence of the various factors on the normal force $N'$ it is not hard to establish their influence on the tangential force $F'$, in so far as the forces $N'$ and $F'$ are connected by the simple relationship $F' = \mu' N'$. 
Experimentally however the values of $F'$ and $N'$ can be determined by extrapolating the force relationship of $F_Z$ and $P_y$ w.r.t. different thickness of uncut layer ($a_1 = a \sin \theta$) to origin i.e. $a_1 = 0$, such that (as shown in Fig. 4.7).

\[ P_Z \text{ at } a_1 = 0 = F' \]
\[ s = 0 \]

and

\[ P_y \text{ at } a_1 = 0 = N' \]
\[ s = 0 \]

The total radial thrust, therefore is

\[ P_yT = P_y + N' \]

4.4.2. Radial Force $P_y$ Versus Cutting Parameters

(a) Effect of Feed, $s$.

As already pointed out that at higher feed level the burnishing effect is observed and it is due to increase in radial thrust force, $P_y$. To prove this, the effect of feed, $s$ on force $P_y$ is shown in Fig. 4.8, for two representative depth of cut 1 mm and 2 mm. It is clearly observed that the value of $P_y$ increases with the increase of both feed 's' and depth of cut 't'. The same pattern is observed for other values of feed and depth of cut. Due to this increase in radial force on the machined surface the ridges get flattened up to provide a smoother surface.
(b) Effect of Cutting Speed, \( V_c \).

The effect of cutting speed on \( P_y \) is varying with the ranges of speed as well as on the values of feed. At some stage it shows definite increase when at some other stages it shows decrease in the values of \( P_y \) with the increase of speed. The pattern is similar to the pattern of chip reduction coefficient. Therefore, the effect of speed on burnishing is not due to increase or decrease in the values of \( P_y \), but due to the improvement in machinability indicated by the decrease in the values of chip reduction coefficient. The improvement in machinability has direct influence on the improvement on surface finish. This finish will further be improved when the value of \( P_y \) is further increased. Therefore any increase in the cutting speed will always be beneficial for surface finish to the extent the surface integrity limit is not exceeded (abusive machining). The effect of cutting speed on \( P_y \) is shown in Fig. 4.9.

(c) Effect of depth of cut, \( t \).

The radial force \( P_y \) increases with the increase in depth of cut as is clear from Fig. 4.8.

4.4.3. **Radial force Versus Tool Geometry**

The principal cutting edge angle, nose radius, rake angle and inclination angle, all affect the radial force. The effect of rake angle on surface roughness is by the improvement in machinability as is the case with cutting speed just discussed.
The nose radius and also the principal cutting edge angle influence the surface finish due to burnishing as both of these parameters directly effect force $P_y$. As the nose radius is increased and also the value of $\phi$ is decreased, the overall effect on the nose flank is the same, i.e. an increase in radial force. Therefore, it is expected that an increase in nose radius and decrease in cutting edge angles would directly cause improvement in surface finish by burnishing. The effect of nose radius and cutting edge angle is shown in Fig.4.10.a,b.

Thus we conclude that feed, depth of cut, nose radius, cutting edge angle affect the improvement in finish by increase of radial force. whereas, speed and lubrication can improve finish by friction reduction and also by machinability improvement. All these are already being explained as factors causing burnishing. Rake angle and other parameters may improve finish by improvement in machinability. This burnishing effected improvement should be accepted up to surface integrity level for satisfactory performance.

4.5 EXPERIMENTAL RESULTS ON DEVIATIONS

Let us assume that the ideal value of Variability index ie. ratio $R_{\text{max}}/R_a = 4$, for zero deviation. And the deviation in finish wrt. the theoretical maximum be $\Delta R$,

$$\Delta R = 4 R_a - R_{\text{th}}, R_a = \text{CLA value, and}$$

$$R_{\text{th}} = R_{\text{max}} = \frac{S^2}{8r} = \text{Theoretical peak to valley height.}$$
And Percentage deviations will be

$$\frac{\Delta R \times 100}{R_{th}}$$

Some values of deviations and percentage deviations are tabulated below in Table 4.1 as obtained experimentally.

<table>
<thead>
<tr>
<th>Speed</th>
<th>36.8 m/min</th>
<th>47 m/min</th>
<th>56.8 m/min</th>
<th>76 m/min</th>
<th>92 m/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.079</td>
<td>6.225(636)</td>
<td>5.425(556)</td>
<td>5.42(556)</td>
<td>4.625(474)</td>
<td>5.225(515)</td>
</tr>
<tr>
<td>0.093</td>
<td>6.65(492)</td>
<td>7.05(522)</td>
<td>6.25(462)</td>
<td>5.05(374)</td>
<td>5.45(403)</td>
</tr>
<tr>
<td>0.101</td>
<td>8.01(503)</td>
<td>8.81(554)</td>
<td>7.61(478)</td>
<td>7.61(478)</td>
<td>6.81(428)</td>
</tr>
<tr>
<td>0.123</td>
<td>8.84(374)</td>
<td>7.64(323)</td>
<td>7.64(323)</td>
<td>8.04(340)</td>
<td>7.64(323)</td>
</tr>
<tr>
<td>0.158</td>
<td>7.7(197)</td>
<td>7.7(197)</td>
<td>6.9(176)</td>
<td>7.3(187)</td>
<td>8.1(207)</td>
</tr>
<tr>
<td>0.202</td>
<td>6.01(94)</td>
<td>5.23(82)</td>
<td>5.63(88)</td>
<td>5.23(82)</td>
<td>4.83(75)</td>
</tr>
<tr>
<td>0.278</td>
<td>1.93(16)</td>
<td>0.93(7.7)</td>
<td>0.33(2.7)</td>
<td>0.33(2.7)</td>
<td>-0.47(-3.9)</td>
</tr>
<tr>
<td>0.317</td>
<td>-0.5(-3.18)</td>
<td>-2.1(-13.4)</td>
<td>-3.1(-19.7)</td>
<td>-3.3(-21.0)</td>
<td>-3.3(-21.0)</td>
</tr>
</tbody>
</table>

The deviation $\Delta R$ in micron and the percentage deviation w.r.t. $R_{th}$ as calculated above are plotted and shown in Fig.4.11 and 4.12. A very sharp fall in $\Delta R$, $% \Delta R$ is observed in the case of feed increase and a marginal fall in $\Delta R$ and $% \Delta R$ is observed in case of speed increase. However, the pattern is very clear and valid for all the speed-feed values. The deviation is negative meaning an improvement in surface finish
due to improvement in machinability condition or burnishing. The amount of deviation consists of a micro-chatter, a machine characteristic factor and a side flow factor. This amount may be as high as 6 times the theoretical ridge height when the feed is small. As the feed is increased the absolute value of deviation increases first but as the ridge height is also more, the percentage will show a decrease. After falling to zero the deviation becomes negative at high feed and high speed showing a considerable improvement in surface finish in sharp contrast to the earlier deterioration. This phenomenon will be more pronounced in the case of speed variation as higher the speed value, the zero deviation will be attained at a lower value of feed. These curves will clearly indicate the actual values of speed and feed for zero deviation i.e. \( \frac{R_{\max}}{R_a} = 4 \) and the effects if the parameters are decreased or increased from that level.

### 4.6. CONCLUSION

This we have seen that the variability factors of surface roughness can be divided into two major categories as (a) those deteriorating the finish from its ideal geometrical level given by \( \frac{R_{\max}}{R_a} < 4 \) and (b) those causing improvement in the surface finish on its geometrical level given by \( \frac{R_{\max}}{R_a} > 4 \) and (c) the ideal level when \( \frac{R_{\max}}{R_a} = 4 \) which is a fixed condition to be determined experimentally.
The first category include the micro-chatter and side flow as the major variable factors which would set the minimum process capability level of the machine tool with respect to production of the surface finish. The factors which cause improvement by burnishing at high feed and high speeds also include other parameters like nose radius, cutting edge angles, rake and friction-lubrication etc. However this improvement in surface finish may be beneficial if and only if it is limited to the extent of surface integrity level set on the basis of a satisfactory level of performance. Exceeding the limit may cause under surface distortions though the surface finish may superficially measure an improvement.

Thus our approach to the different variability factors should also be different so that we can get the best acceptable result by appropriate selection of parameters determining such factors and at optimum cost considerations.

The material factors however is not considered here as the same will be dealt with in detail separately in the next chapter with experimental results.
Fig. 4.1 Schematic of Side flow.

Fig. 4.2 Side Flow a/A OR h/t (Radhakrishnan)
Fig. 4.3 Effect of Rake Angle on Side flow.
( Radhakrishnan )

Fig. 4.4 Effect of Speed on Side flow and Surface finish.
( Radhakrishnan )
**Fig. 4.5** Burnishing Effect Scheme

$$R_{\text{max}} - R_{\text{ac}} = R_{\text{max}} - 4 R_a$$

**Fig. 4.8** Radial Force Vs. Feed.
Fig. 4.6 Effect of $\tau_s$, $L$, $\beta$, $\mu'$ on Normal Force, $N$. (Zorev)

Fig. 4.7 Extrapolation to find $F'$ and $N'$. (Zorev)
Fig. 4.9 Effect of Speed on Radial Force, $P_y$ (Zorev)

Fig. 4.10 Effect of Principal cutting edge Angle, $\phi$ (a) and Nose radius, $r$ (b) on Cutting Forces mainly Radial Force $P_y$. (Bhattacharyya)
DEVIATIONS IN $R_{\text{max}}$ VS FEED AND SPEED

**Fig. 4.11**