Surface Roughness Modeling Of Titanium Alloy Grinding

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Abstract - Titanium and its alloys have found applications in aerospace industry, chemical industry, biomedical engineering and marine industries due to high specific strength (strength-to-weight ratio) and excellent corrosion resistance. Despite good mechanical properties grinding of Titanium and its alloys is difficult due to large grinding force, poor heat transfer capability and high chemical reactivity with ambient gases. To assess the effectiveness of titanium grinding, experimental or theoretical evaluation of surface roughness is essential. The experimental methods of surface finish evaluation are costly and time consuming. Hence, a predictive surface roughness model is developed for the grinding of titanium alloy. Which relates the surface roughness values to the process variables, like speed, depth of cut etc. To account for high randomness associated with the process, probabilistic approach is used to predict the surface roughness. The effects of plowing and the elastic deflections on surface roughness are taken into account. Also, the ground surface and grinding wheel profile are simulated using MATLAB, and surface roughness is calculated. The results obtained are then validated by conducting grinding experiments

***Key Words*: Surface Roughness, Grinding, MATLAB, Surface Roughness Modeling, Chip Thickness ratio.**

1.INTRODUCTION

The functional performances of any engineering component depends largely on the properties of the surface as well as the zones immediately under the surface. Different factors that contributes to performance of surface are shape, material properties, residual stresses, surface roughness etc. The overall quality is therefore, dependent upon the final process by which it is produced. Grinding process is usually considered as the final operation in most of the manufacturing processes, due to its ability of producing good surface finish and required dimensional tolerances. Titanium and its alloys have found applications in aerospace industry, chemical industry, biomedical engineering and marine industries due to high specific strength (strength-to-weight ratio) and excellent corrosion resistance. Its density is 60% of that of steel. Amongst all Ti alloys Ti-6Al-4V is the most widely used titanium alloy which is a mixed alpha-beta structure having optimum density, creep strength and fabric ability. Ti is a transition element which changes from alpha (HCP) to beta (FCC) at 883°C. A large no. of surface roughness models has been developed, which are based upon certain assumptions that may not be valid for actual working conditions. Titanium being a ductile material, is severely affected by the plowing up of material, by the action of grits on to the surface. Hence, the actual value of surface roughness depends largely upon the extent of plowing during the grinding process. Also, there are elastic deflections of the work piece as well as grinding wheel during the grinding process. These deflections will change the effective depth of cut as well as the contact length in grinding contact zone, which will lead to changes in the value of undeformed chip thickness. The surface roughness value is a direct function of undeformed chip thickness, and hence it becomes necessary to consider the effect of these factors while deriving the surface roughness models. Apart from the analytical models, another approach for predicting surface roughness is the development of programming codes in MATLAB for simulating the grinding wheel profile as well as the ground surface. Using these images, we can directly predict the surface roughness values, by giving the kinematic conditions like speed, feed, and depth of cut, material properties etc. as the input variables. The results obtained by the analytical models and the simulations are to be compared with the experimental surface roughness values, by conducting grinding experiments on CNC grinding machine.

2. ANALYTICAL MOEDLING

The analytical model developed in this investigation is to be considered as the early attempt that considers the wheel structure, wheel grit size, work material properties, depth of cut etc. to calculate undeformed chip thickness and the surface roughness. Hence, considering the complex nature of grinding process, the following assumptions have been made:

i. The wheel dressing effect has not been considered in this analysis, and thus the grain distribution with and without dressing is considered to be same.
ii. Analysis is done for no lubrication condition i.e. dry work environment.
iii. The abrasive grits shape is assumed conical.
iv. The effect of burn-offs and the effect of rubbing grits on the surface roughness is neglected.

2.1 Determination of Contacting Grits

The number of grains on on the grinding wheel surface in unit length is given by:

$$N_{gl} = \frac{(volume\ fraction\ of\ abrasives)^{\frac{1}{3}}}{d_{g\ mean}}$$

Using the number of grits, per unit length, we can calculate number of grits per unit area by following formula:

$$N_{ga} = N_{gl}{}^{2}$$

The values of mean grain diameter and volume fraction of abrasives can be obtained for a specific grinding wheel using following tables:

Table -1: $d_{g\,max}$, $d_{g\,min}$, and $d_{g\,mean}$ for different grain sizes [13]

Mesh Size	20	24	30	36	46	54	60	70	80	90	100
$d_{g\,max}$(mm)	0.937	0.761	0.587	0.475	0.355	0.292	0.256	0.212	0.179	0.151	0.141
$d_{g\,min}$(mm)	0.761	0.587	0.475	0.353	0.292	0.256	0.212	0.179	0.151	0.143	0.115
$d_{g\,mean}$(mm)	0.851	0.675	0.531	0.416	0.322	0.272	0.234	0.195	0.166	0.146	0.129

Table -2: Volume fraction of abrasive based upon structure no. [13]

Structure number	0	1	2	3	4	5	6	7	8
Abrasive volume fraction	0.68	0.64	0.60	0.58	0.56	0.54	0.52	0.50	0.48

2.2 Distribution Of Grits

The surface profile obtained after grinding consists of grooves left after grinding, and the size of grooves is equal to that of undeformed chip thickness values. Also, the piling up of work material due to plowing action of grits contribute to the surface roughness, thus obtained. Taking into consideration, the random variation of the sizes of individual grits, the undeformed chip thickness values will also be different for different grits, and hence certain probability distribution must be assumed for individual grits. The Rayleigh probability density function can be used to approximate the size of individual grits:

$$f(h) = \begin{cases} -\dfrac{h}{\beta^2} e^{-\frac{h^2}{2\beta^2}}, & h \geq 0 \\ 0, & h < 0 \end{cases}$$

The parameter β, completely defines the Rayleigh PDF, and is a function of material properties, dynamic effects, wheel microstructure etc. The surface roughness values obtained by analytical model will be a direct function of the parameter β. Further, the value of this parameter is known in terms of chip thickness, as per following equations:
The expected value and variance of above equation are given by:

$$E(h) = \sqrt{\frac{\pi}{2}}\beta, and$$

$$Sd(h) = \sqrt{0.428}\beta$$

The following figure1 represents the schematic view of grain size distribution in the unit length of wheel surface. On the left, is the curve for Rayleigh distribution.

Fig.3.1 Distribution of grits

The magnitude of E(h) can be calculated by Rayleigh probability density function. The better illustration of the grit distribution, in accordance with Rayleigh probability density function can be achieved through following figure:

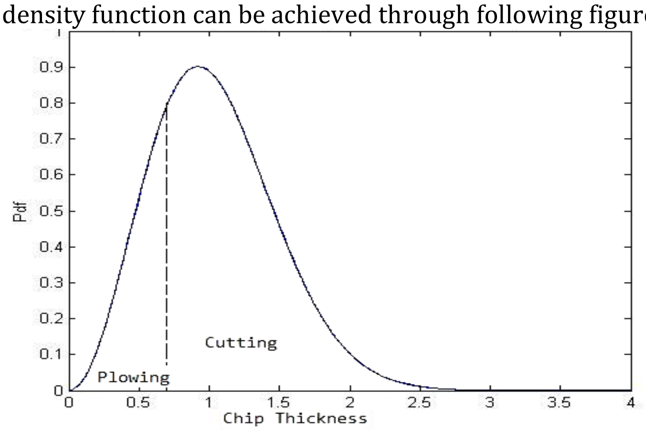


Fig. 3.2 Rayleigh probability distribution function

2.3 Elastic Deflection

During grinding, the grits as well as the work piece material will undergo elastic deflections. Hence, the effective depth of cut for the individual grit will be far much different than the provided depth of cut, and thus the contact length, as well as undeformed chip thickness will be different from that given by empirical formulas:

Fig. 3.3 Elastic deflection model for grits

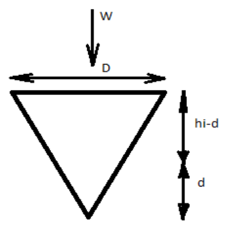
To calculate the magnitude of these elastic deflection values, kumar and shaw[14] have given separate formulas for local wheel deflection, as well as local work deflection, which are obtained by equating the magnitudes of initial and final lengths of contact zones. The formulas are as follows:

wheel deflection:

$$y_s = \frac{0.095(1+\vartheta)F_t D}{l' b E_s} \qquad \ldots\ldots 2$$

And, Local work deflection:

$$y_w = \frac{-2F_t}{\pi E_w b} ln\left(\frac{l'}{2}\right) \qquad \ldots\ldots 3$$



Here, υ is the poisson's ratio for the grinding wheel. The value of tangential force components can be calculated easily by using a dynamometer, for initial stages. Further, force modeling data can also be used to calculate the force components, under different working conditions. The calculations for l' i.e. actual contact length are shown in next paragraphs, by considering the thermal effects on the contact length. The total deflection is given by the sum of the local work and local wheel deflections.

3.4 Calculation for Contact Length

Considering the high energy consumption during the process of grinding, it can be interpreted that a large amount of heat is produced during the process. This heat gets accumulated at wheel-work piece contact zone, and thus raising the local temperature. Due to this increase in temperature, the actual contact length will be much different from that of real contact length. To take into account the thermal effects, Setti et al [13] have derived a formula for actual contact length, by modifying the surface roughness factor in the contact length formula given by Rowe and Qi [8].

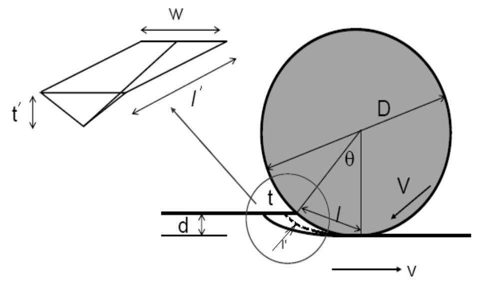


Fig.3.4 Chip thickness model

The formula is given as follows:

$$l^2 = \left[\left(\frac{T_m}{R}\right)^2 * 8F_n(K_s + K_w)D\right] + {l_g}^2$$

here lg is the geometric contact length given by:

$$l_g = \sqrt{Da_e}$$

Where ae is the depth of cut. The value of Fn can be calculated easily by using dynamometers. Further, the value of Tm is given by Malkin and Guo[15] as follows:

$$T_m = c * \pi\sqrt{p}$$

Where p is the peclet no. and is given by:

$$p = \frac{v_w l_g}{4\theta}$$

θ is known as the thermal diffusivity and can be calculated by formula:

$$\theta = \frac{k}{\rho c_p}$$

Where, ρ is the density of work piece, and k is the thermal conductivity. The value of c in Malkin's formula is given by following formula:

$$c = 1.05 \; if \; p > 10$$

$$c = \frac{0.94}{\pi}\sqrt{6.283 + \frac{p}{2}} \quad if \; 0.2 < p < 10$$

$$c = 0.76 \; if \; p < 0.2$$

Further, for dry condition, heat partition ratio, R can be given by the following equation:

$$R = \left(1 + \frac{0.96 k_g}{\beta_w \sqrt{r v_c}}\right)^{-1}$$

The value of β_w is given by the following formula:

$$\beta_w = \sqrt{c_p \rho k}$$

And r is the mean grit radius, given by the formula:

$$r = \frac{d}{2}, d = \frac{68}{M}$$

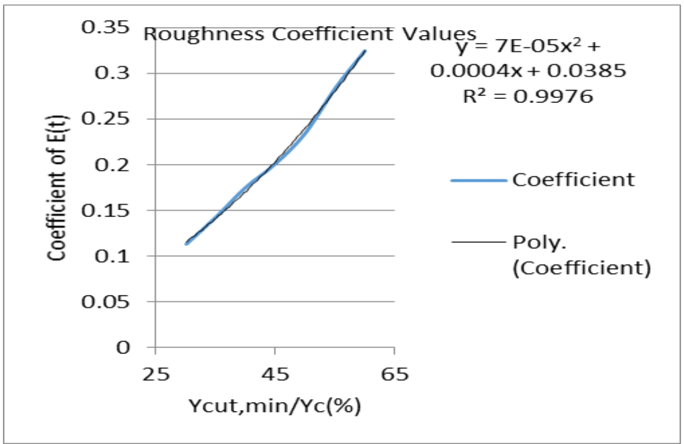
Where M is the mesh size, for a particular grinding wheel

3.6. Surface Roughness Calculation

Using different formula's we found different results
The following table shows the value of coefficient for different $y_{cut,min}$ values:

$Y_{cut,min}/y_c$ (%)	Coefficient of $E(R_a)$ (for β)	Coefficient of $E(R_a)$ (for $E(t)$)
30	0.1418	0.1132
35	0.1793	0.1431
40	0.2200	0.1756
45	0.2522	0.2012
50	0.2940	0.2346
55	0.3554	0.2836
60	0.4068	0.3246

Table 3 Coefficients of β and E(t) in surface roughness formula



Roughness Coefficient Values

After calculating these coefficients, next step is to calculate the value of undeformed chip thickness. To take into account, the elastic deflections, first we have to calculate grit and work contact deflections, as per equation 2 and 3. For this, values of force components must be calculated. Initially, force values have been measured by conducting experiments, but in actual usage, the force models may be used. The normal and tangential force components at different depth of cuts, as obtained by Kistler dynamometer, for the given grinding parameters are:

S.No.	Depth of Cut	Speed ratio	Tangential Force	Normal Force
1	3	100	2.74	8.04
2	6	100	12.88	37.04
3	9	100	25.41	70.85
4	12	100	32.97	92.2
5	15	100	53.3	129.94

Normal and tangential force components

Through this force components, we can easily calculate the values of actual contact length, as well as the value of elastic deflections. Table 5 represents the values of elastic deflections. The total deflection will be the difference of the two values.

S.No.	Depth of Cut	Speed ratio	Wheel deflection (μm)	Workpiece Deflection(μm)	Total Deflection(μm)
1	3	100	1.98	0.05	1.93
2	6	100	2.35	0.08	2.27
3	9	100	3.12	0.11	3.01
4	12	100	3.48	0.15	3.33
5	15	100	3.87	0.21	3.66

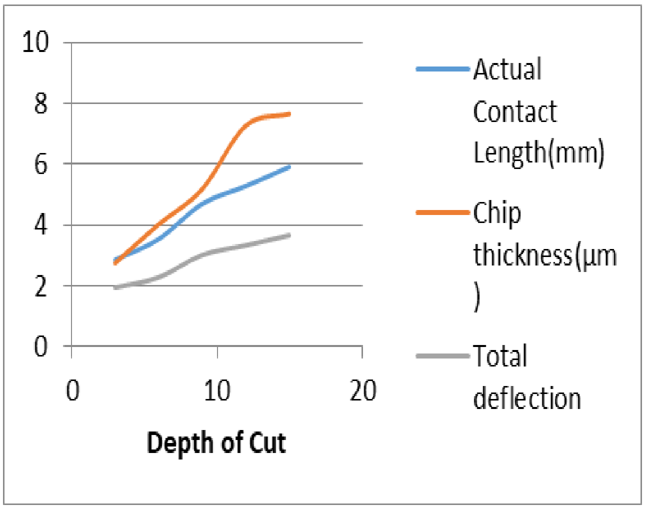
Wheel and Work piece contact deflections

Further, Table 6 represents the value of actual contact length, and the undeformed chip thickness. This chip thickness value takes into account the effect caused by the thermal effects:

S.No.	Depth of Cut	Actual Contact Length(mm)	Undeformed chip thickness(μm)
1	3	2.842	2.7642
2	6	3.523	4.0371
3	9	4.681	5.1872
4	12	5.263	10.1098
5	15	5.895	11.2859

Actual contact Length and depth of cut

Following graph shows the variation of actual contact length, chip thickness and total deflection with change in depth of cut:



Variation of chip thickness, actual contact length, and total deflection with depth of cut Hence, after calculating actual chip thickness value, next step is to calculate the value of roughness coefficient from figure 7, for a given depth of cut. Now to relate the value of depth of cut with a particular roughness coefficient, we have to calculate the ratio of critical depth of cut to the actual depth of cut, and then calculating the value of roughness coefficient corresponding to this ratio, by using graph shown in figure 7. The ratio of critical depth of cut to actual, represents the particular value, below which the plowing will takes place, and above which cutting will takes place. The following Table 7 represents the value of depth ratios, and the corresponding roughness coefficients.

After calculating the desired roughness coefficient values, final step is to calculate the value of surface roughness, by using equation 6. The values are shown in Table 8:

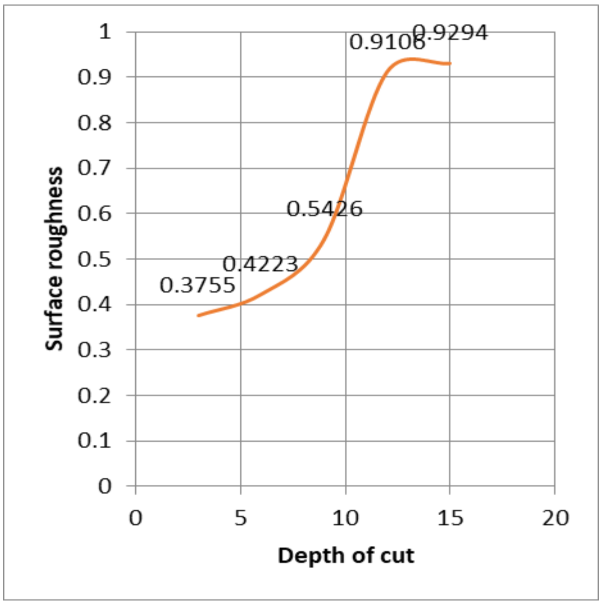
S.No.	Depth of Cut(μm)	Critical depth of cut(μm)	Ratio (DOC/CDOC)	Roughness Coefficient
1	3	1.42	0.4733	0.2112
2	6	3.23	0.5383	0.2742
3	9	5.25	0.5833	0.3128
4	12	7.15	0.5958	0.3246
5	15	9.52	0.6346	0.3375

Desired Roughness Coefficient Values

After calculating the desired roughness coefficient values, final step is to calculate the value of surface roughness, by using equation 6. The values are shown in Table

S.No	Depth of cut(μm)	Undeformed chip thickness	Roughness Coefficient	Critical Ratio	Surface Roughness(μm)
1	3	2.7642	0.2112	0.6433	0.3755
2	6	4.0371	0.2742	0.3783	0.4223
3	9	5.1872	0.3128	0.3344	0.5426
4	12	10.1098	0.3246	0.2775	0.9106
5	15	11.2859	0.3375	0.2440	0.9294

Predicted Surface Roughness values



Predicted Surface Roughness

The above table shows the values of predictive surface roughness values using the developed analytical model.

3.7 Simulated Wheel Surface

The surface shown below is simulated using MATLAB by approximating the grit distribution to be random in nature. The different regions of the profile are explained in attached chart. The red zones represent cutting grits, which will then be used to plot the ground surface.

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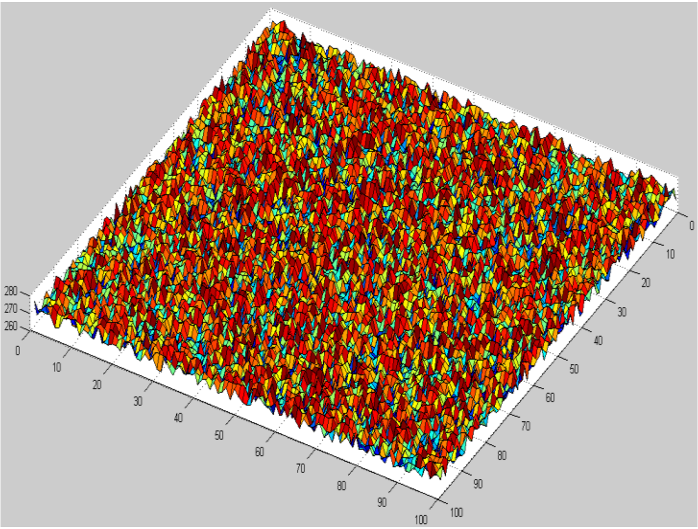
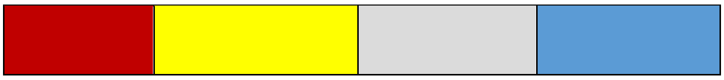
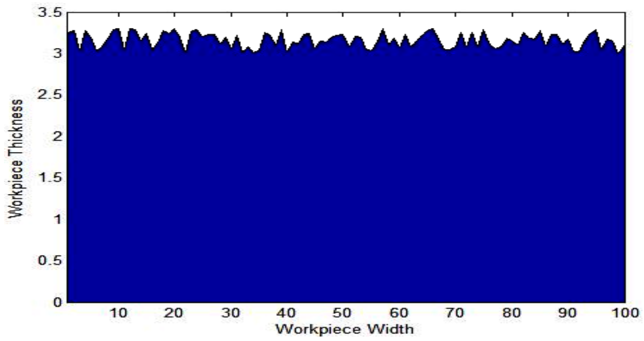


Grit simulation

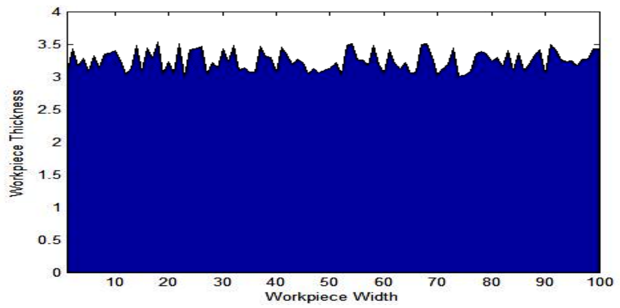


Cutting Grit Contacting grits Bond Material Plowing Grits

3.8 2D Surface Profile



2D surface profile at 3μm DOC



2D surface profile at 6μm DOC

4: EXPERIMENTAL VALIDATION

The developed analytical surface roughness model and the simulations results has been validated by performing a series of grinding experiments on CHEVALIER SMART H1224 CNC surface grinder. After each experiment, surface roughness has been measured using TALYSURF profile meter. The experiments have been conducted with a conventional C60K5V grinding wheel. The properties of Ti-6Al-4V work piece material used for experimental work are as follows:

Property	Value
Density	4.43gm/cc^3
Modulus of Elasticity (W/P)	113GPa
Poisson's Ratio (W/P)	0.342
Modulus of Elasticity (Wheel)	25Gpa
Poisson's Ratio (Wheel)	0.22
Wheel Dimension	350mm*50mm*127mm

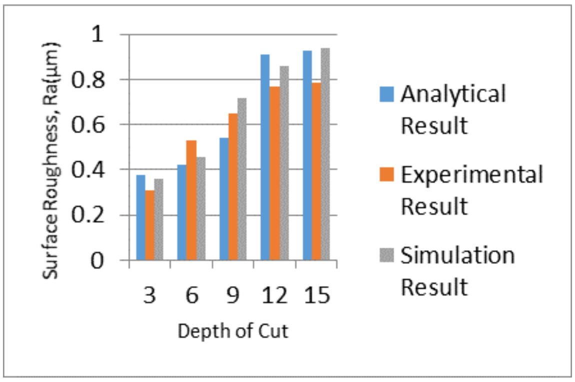
Wheel and Work piece material properties

The grinding experiments are conducted at depth of cut values of 3, 6, 9, 12, 15 μm, and the speed ratio of 100. Before conducting experiments, fine dressing operation has been performed on the wheel with dressing depth of 10 mm, and dressing lead of 10mm/min.

The following table shows the values of the surface roughness values obtained, as well as percentage deviation of the modelled surface roughness value and the simulated surface roughness value from the experimentally calculated value. Further, the bar chart clearly represents the difference between the predicted values and the, experimentally calculated values:

S.No.	Depth of cut	Analytical Ra(μm)	Experimental Ra(μm)	Simulated Ra(μm)	Percentage Error(Analytical)	Percentage error(Simulation)
1	3	0.3755	0.3056	0.3612	22.87	18.19
2	6	0.4223	0.5302	0.4561	-20.35	-13.98
3	9	0.5426	0.6461	0.7148	-16.02	10.63
4	12	0.9106	0.7653	0.8564	18.98	11.90
5	15	0.9294	0.7876	0.9355	18.00	18.78

Predicted and Experimental results



Predicted and Experimental Results

5. CONCLUSIONS

1) An analytical surface roughness model is developed for the grinding of titanium alloys that takes into account the effect of plowing grits as well as the effect of elastic deflections.
2) A MATLAB code is generated, to simulate the wheel surface, and the 2D ground surface, and then surface roughness value is calculated for different depth of cut values.
3) The surface roughness values obtained by the analytical model and the simulations are then validated by conducting grinding experiments on Ti-6Al-4V work piece, using C60K5V grinding wheel.
4) The results obtained are in close correlation with the experimental values, and the average errors of 19.24% and 14.7% are obtained by analytical model and simulations respectively

5.1Scope For Future Work

The effect of rubbing grits and burn-offs on surface roughness can be included, to make the model more accurate.
The grits shape can be more accurately assumed, by taking the contact stylus data, in place of assuming the conical shape of the grits.
While generating the MATLAB code, the trajectory is assumed to be trochoidal in nature, which can be further modified by taking a combination of different curve equations, to make the results more accurate.

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