Comprehensive Study of Surface Roughness Model of Workpiece in Grinding Process

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Abstract—This article presents a comprehensive study of surface roughness model of workpieces in grinding process. Studies show that cutting parameters are often chosen as input parameters to build surface roughness model. However, the surface roughness model in each processing condition has different values. As a result, this study has proposed a method for building a surface roughness model of a workpiece when studying the grinding process by experimental method.

Keywords—grinding process, surface roughness model, RSM

I. INTRODUCTION

The surface roughness of a workpiece is a very important parameter to evaluate the surface quality of the workpiece. When the surface of a machine part is machined by grinding, the surface roughness of the part is more clearly shown as an important parameter, because grinding is often the final processing method for surfaces of workpiece that require small surface roughness. For the purpose of processing the surface of the workpiece with small roughness, many studies have been published. Among those studies, the authors usually focus on two methods. Firstly, building a surface roughness model of a workpiece based on theoretical studies [1-13]. Secondly, building a surface roughness model of a workpiece based on experimental studies. With empirical methods, studies often give the surface roughness model of the workpiece in the form of regression equations which show the relationship between the surface roughness of the workpiece and the parameters of machining process. From that relationship, we can determine the value of technological parameters to process the surface of the workpiece in order to achieve the required surface roughness value. This method is commonly known as the Response Surface Method (RSM).

This article conducts the comprehensive study of some surface roughness models in published studies, thereby determining the parameters which are commonly used as input parameters when studying surface roughness by RSM.

II. RESPONSE SURFACE METHOD

Response surface method (RSM) is a combination of statistical theory and mathematical model, which is very useful in the modelling and analysing the technical problems. The main objective of RSM is to determine the optimum value of the target surface affected by many different initial parameters. Furthermore, RSM also allows control of input parameters to ensure the surface reaches a certain value. In RSM, the relationship between desired response and the input parameters is expressed in the following form [14, 15].

\[ Y = F(x_i) \]  \hspace{1cm} (1)

For the specific case of this study, \( Y \) is the surface roughness value of the part; \( F \) is the response function; \( x_i \) is input parameter. In engineering, most of the relationship between the target surface roughness and the input parameters can be expressed and represented by a second order model [14]. This model works quite well across the entire range of input variables. Consequently, the expression (1) is written in the following form.

\[ Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \varepsilon \]  \hspace{1cm} (2)

In which: \( Y \) is corresponding response; \( x_i \) is \( (i^{th}) \) value of the input parameters; the quantities \( \beta \) are regression coefficients; \( \varepsilon \) is residual measure.

III. LITERATURE OVERVIEW

Table 1 presents a summary of some published studies on surface roughness of workpieces in grinding process, including: type of grinding wheel, type of processing materials, method of grinding, input parameters, conclusions or comments made in those studies. Table 2 presents some roughness models of the workpiece (regression model) corresponding to the studies mentioned in Table 1.
### Table 1. Summary of some published studies

<table>
<thead>
<tr>
<th>Conclusions/Discussions</th>
<th>Eq. in Table 2</th>
<th>Grinding wheel</th>
<th>Workpiece material</th>
<th>Grinding method</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>- The error between experimental and predicted values at the optimal combination of parameter settings for within 4.30%.</td>
<td>(3)</td>
<td>$\text{Al}_2\text{O}_3$ wheel</td>
<td>EN 24 steel</td>
<td>surface grinding</td>
<td>[16]</td>
</tr>
<tr>
<td>- The optimal combination of parameter settings are wheel speed of 850RPM, table speed of 15m/min and depth of cut of 11.94µm for achieving the required minimum surface roughness.</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>The feed rate and depth of cut have significant effects on surface roughness values.</td>
<td></td>
<td>$\text{Al}_2\text{O}_3$ wheel</td>
<td>OHNS</td>
<td>cylindrical grinding</td>
<td>[17]</td>
</tr>
<tr>
<td>- First order surface roughness model may be adequate for cylindrical grinding operation with parameters work speed, feed and depth of cut. The job dimensions and the parameters for experiments can be fixed after selecting the machine, the work material and the grinding wheel.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>- A second-order response surface model for surface roughness can be developed from the observed data. This will give 95% confidence level for the model.</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>- Response surface methodology provides a large amount of information with a small amount of experimentation.</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>- A second-order response surface model for surface roughness has been developed from the observed data. The predicted and measured values are fairly close, which indicates that the developed model can be effectively used to predict the surface roughness on the machining of MMCs with 95% confidence intervals. Using such model, one can obtain a remarkable savings in time and cost.</td>
<td>(4)</td>
<td>-</td>
<td>6061Al</td>
<td>cylindrical grinding</td>
<td>[19]</td>
</tr>
<tr>
<td>- Increasing the hardness, improves surface finish of workpiece.</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>- Response surface methodology provides a large amount of information with a small amount of experimentation.</td>
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</tr>
<tr>
<td>The depth of cut followed by flow rate and nozzle angle was most influencing parameters on surface roughness and material removal also.</td>
<td></td>
<td>A60 M6 VCNM</td>
<td>SAE 8620 grade steel</td>
<td>cylindrical grinding</td>
<td>[20]</td>
</tr>
<tr>
<td>All of input parameters have a significant effect on surface roughness.</td>
<td>(5)</td>
<td>22A60L6V6 3L</td>
<td>9SMn28</td>
<td>centerless grinding</td>
<td>[21]</td>
</tr>
<tr>
<td>The depth of cut has a greater effect on the surface roughness and feed has a medium effect while dressing depth of cut has minimal</td>
<td>(6)</td>
<td>A60V5V</td>
<td>AISI 1080</td>
<td>surface grinding</td>
<td>[22]</td>
</tr>
</tbody>
</table>
effect on surface roughness. Therefore, huge care has to be taken while selecting depth of cut in the grinding process.

- The depth cut was influenced the out range of surface roughness. When depth of cut is minimum the value of surface roughness is also minimum. Based in the input and output results can predict the optimal value of surface roughness that derived in the final equation.

| (7) | AISI 4140 Steel | cylindrical grinding |
| (8) | SiC grain | grinding and polishing process |
| (9) | green silicon carbide with grit size of 120 microns | D2 steel | work roll grinding |
| (10) | CBN grinding wheel with grain size of 270 | SK-41C tool steel | micro-grinding process with compressed air |
| (11) | A460L5V20 | SS430 Material | cylindrical grinding |
| (12) | Al$_2$O$_3$ wheel | OHNS Material | cylindrical grinding |
| (13) | Cn80.TB1.G, V$\_1$, 500.150. 305x35m/s | 20X-carbon infiltration steel | plunge centerless grinding |
| (14) | metallic OFSiC | surface |

All of input parameters have a significant effect on surface roughness.

- When depth of cut and spindle speed is increased the MRR is increased and the grits become dull. The dull grits led to raised grinding force and effect the geometry of work surface. Such conditions present excessive heating of surface, burn marks and may be small cracks.

- It is possible to predict the surface roughness and material removal rate before conducing grinding process.

- The surface roughness increases with an increase in the feed rate and depth of cut had significant effects on surface roughness during the micro-grinding process, but their behaviours were different. The surface roughness values increased monotonically with increase in the feed rate.

- By contrast, the response surface of the surface roughness in terms of depth of cut and air temperature had a saddle shape, which is very different from that for feed rate and air temperature.

All of input parameters have a significant effect on surface roughness.

All of input parameters have a significant effect on surface roughness.

- The mathematical models can be successfully used to predict the surface roughness value for any combination of the feed rate, grit size, cutting speed and depth of cut within the range of the performed experimentation.
increase in feed and depth of cut. When the feed and depth of cut are increased, the increase in material removal rate and the increase in chip thickness account for the increase of surface roughness.

- Surface roughness decreases with an increase in wheel speed.

<table>
<thead>
<tr>
<th>All of input parameters have a significant effect on surface roughness</th>
<th>CBN wheel</th>
<th>AISI 1045 steel</th>
<th>cylindrical grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>bonded diamond grinding wheel</td>
<td>advanced ceramic material grinding</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The cutting fluid (water soluble oil) was most influencing factor for EN8 materials followed by work piece speed and depth of cut.

- Higher work piece speed and higher the depth of cut improves surface finish when grinding in water soluble oil. With emulsion coolant, better surface finish is obtained at higher work piece speed and higher depth of cut with manual feed.

- Water soluble oil contain higher flow ability with a medium viscosity, when pure oil gives poor flow ability with a high viscosity and pure water gives higher flow ability with poor viscosity. this study shows that, due to high flow ability and medium viscosity gives maximum value of surface roughness.

- Water soluble oil gives better surface roughness than pure water due to oil smoothened cutting action. Pure oil gives higher surface roughness than water soluble oil because it only contains high viscosity oil cutting action.

- As the work piece speed increases the rubbing of the abrasive grain also increased and it leads to reduced surface roughness. Depth of cut increases from lowest to highest level, surface roughness was reduced.

- In dry grinding process, the depth of cut if found to be significant in ANOVA of surface roughness.

<table>
<thead>
<tr>
<th>(15) CBN wheel</th>
<th>AISI 1045 steel</th>
<th>cylindrical grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>bonded diamond grinding wheel</td>
<td>advanced ceramic material grinding</td>
<td></td>
</tr>
</tbody>
</table>

- Cylindrical grinding is a finest method to produce improved surface quality in machined components. Whenever the input parameters get deflected, it reflects on the outcome of the component. It may be depth of cut, cutting speed.

- In bronze and gunmetal materials, increasing depth of cut reduces the surface finish of component.

- For EN-31 material in case of without hardening, the mean average roughness shows that depth of cut contributes highest effect on the surface roughness, followed by table speed.

<table>
<thead>
<tr>
<th>EN-31 material</th>
<th>surface grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>bonded diamond grinding wheel</td>
<td>advanced ceramic material grinding</td>
</tr>
</tbody>
</table>

- Aluminum oxide White grinding wheel | EN8 material | cylindrical grinding |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>bonded diamond grinding wheel</td>
<td>advanced ceramic material grinding</td>
<td></td>
</tr>
</tbody>
</table>

- In bronze and gunmetal materials, increasing depth of cut reduces the surface finish of component.

- For EN-31 material in case of without hardening, the mean average roughness shows that depth of cut contributes highest effect on the surface roughness, followed by table speed.
and coolant flow rate.

- For EN31 with hardening, the mean average roughness shows that table speed contributes highest effect on the surface roughness, followed by depth of cut and coolant flow rate.

All of input parameters have a significant effect on surface roughness

| Traverse speed and the depth of cut are significant factors that affect the surface roughness of Inconel 718. However, the number of passes does not seem to have any significant effect. The traverse speed is the most significant factor that affects the surface roughness of Inconel 718, followed by the depth of cut. |
|---|---|---|
| (19) | - | Inconel 718 material | surface grinding | [37] |

Table 2. Surface roughness models

<table>
<thead>
<tr>
<th>Regression model</th>
<th>Input parameters</th>
<th>Eq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_a = 3.10845 \times N_c - 0.031132 \times v_w - 0.021647 \times t + 0.00000 \times N_c^2 + 0.00265 \times v_w \times t$</td>
<td>$N_c$ is grinding wheel speed [rev/min]; $v_w$ is table speed [m/min]; $t$ is depth of cut [mm]</td>
<td>(3)</td>
</tr>
<tr>
<td>$R_a = 7.79696 - 0.118088 \times A - 7.86756 \times B - 0.00101748 \times C + 0.00051371 \times A^2 - 7.95455 \times B^2 - 3.13131 \times 10^{-7} \times C^2 + 0.0240385 \times A \times B + 1.37821 \times 10^{-5} \times A \times C + 0.003125 \times B \times C$</td>
<td>A is Hardness [BHN]; B is depth of cut [mm]; C is flow rate [ml/min]</td>
<td>(4)</td>
</tr>
<tr>
<td>$R_a = 1.22 + 0.041 \times h + 0.27 \times f_d - 4.722 \times 10^{-3} \times n_c + 0.035 \times v_{fa} - 0.07 \times h^2 - 0.09 \times f_d^2 - 0.069 \times n_c^2 - 0.027 \times v_{fa}^2 + 1.25 \times 10^{-3} \times h \times f_d + 7.917 \times 10^{-3} \times h \times n_r + 1.25 \times 10^{-3} \times h \times v_{fa} + 1.25 \times 10^{-3} \times f_d \times n_r + 4.167 \times 10^{-4} \times f_d \times v_{fa} + 0.02 \times n_r \times v_{fa}$</td>
<td>h is component height [mm]; $f_d$ is dressing feed-rate [mm/min]; $n_c$ is control wheel speed [rev/min]; $v_{fa}$ is In-feed speed [m/s]</td>
<td>(5)</td>
</tr>
<tr>
<td>$R_a = 0.39375 - 4.385 \times D - 0.345 \times F + 0.325 \times \frac{D}{D_d} + 2 \times D + F + 5 \times D \times D_d + 5 \times F \times D_d + 19.3 \times D^2 + 0.575 \times F^2 + 32.5 \times D_d^2$</td>
<td>D is depth of cut [mm]; F is feed rate [mm]; $D_d$ is dressing depth of cut [mm]</td>
<td>(6)</td>
</tr>
<tr>
<td>$R_a = 0.17683 + 4.89633 \times 10^{-4} \times N + 1.75037 \times D + 4.72369 \times 10^{-3} \times T$</td>
<td>$N$ is workpiece speed [rev/min]; $D$ is depth of cut [μm]; $T$ is time [min]</td>
<td>(7)</td>
</tr>
<tr>
<td>$R_a = 1.20772 - 2.74927 \times 10^{-3} \times P - 0.24117 \times F - 0.075175 \times V_c + 0.2705 \times V_w + 8.298 \times 10^{-6} \times P^2 + 0.049825 \times F^2 + 3.11404 \times 10^{-3} \times V_c^2 + 0.74561 \times V_w^2 - 1.66667 \times 10^{-4} \times P \times F + 4.16667 \times 10^{-5} \times P \times V_c - 1.25 \times 10^{-3} \times P \times V_w + 6.07153 \times 10^{-18} \times F \times V_c - 0.025 \times F \times V_w - 0.01875 \times V_c \times V_w$</td>
<td>$P$ is abrasive size; $F$ contact force [F/N]; $V_c$ is belt linear velocity [m/s]; $V_w$ is feed rate [m/min]</td>
<td>(8)</td>
</tr>
</tbody>
</table>
\( R_a = 0.0786 - 0.0042 \cdot W_e - 0.00079 \cdot J_s + 0.0025 \cdot T_s \\
+ 0.0024 \cdot d - 0.0022 \cdot D_p + 0.0021 \cdot D_e - 0.0036 \cdot W_e^2 \\
- 0.000486 \cdot J_s^2 - 0.000944 \cdot T_s^2 + 0.0032 \cdot d^2 \\
- 0.0024 \cdot D_p^2 - 0.00082 \cdot D_e^2 - 0.0027 \cdot W_e \cdot J_s \\
+ 0.0015 \cdot W_e \cdot T_s + 0.00025 \cdot W_e \cdot d - 0.00125 \cdot W_e \cdot D_p \\
- 0.0002 \cdot W_e \cdot D_p + 0.00025 \cdot J_s \cdot T_s \\
- 0.0015 \cdot J_s \cdot d + 0.0034 \cdot J_s \cdot D_p - 0.00137 \cdot J_s \cdot D_e \\
+ 0.00012 \cdot T_s \cdot d - 0.0015 \cdot T_s \cdot D_p - 0.00031 \cdot T_s \cdot D_e \\
- 0.0045 \cdot d \cdot D_p - 0.000375 \cdot d \cdot D_e - 0.00137 \cdot D_p \cdot D_e \\
\)  

\( W_e \) is wheel speed [rev/min];  
\( J_s \) is work speed [rev/min];  
\( T_s \) is traverse speed [m/min];  
\( d \) is in-feed [\( \mu m \)];  
\( D_p \) is dress depth [\( \mu m \)];  
\( D_e \) is dress feed [mm/min]  
\( R_a \) is cutting speed [m/s];  
\( \beta \) is center height angle (°);  
\( S_{sd} \) is dressing feed-rate [mm/min];  
\( S_k \) is feed speed [μm/s];  
\( v_{dd} \) is control wheel velocity [m/min]  
\( S_{dd} \) is depth of cut [mm];  
\( R \) is job rotating speed [rev/min];  
\( f \) is feed rate [mm/s]  
\( R_a \) is depth of cut [mm];  
\( R_a \) is depth of cut [mm];  
\( R_a \) is depth of cut [mm];  
\( R_a \) is depth of cut [mm];  
\( F \) is table feed [mm/min];  
\( D \) is depth of cut [mm];  
\( N \) is wheel speed [rev/min]  
\( R_a \) is infeed [μm];  
\( v_s \) is wheel speed [m/s];  
\( v_w \) is work speed [m/s]  
\( R_a \) is work piece speed [rev/min];  
\( A \) is cutting speed [m/s];  
\( B \) is depth of cut [μ];  
\( C \) is table feed [mm/min];  
\( D \) is MQL with Nano particles [% by wt]  
\( R_a \) is table speed [mm/min];  
\( D \) is depth of cut [μm]
The data in tables 1 and 2 show that: (1) The studies often select the cutting parameters as input parameters in experimental studies to build a surface roughness model. (2) For most grinding methods (surface grinding, cylindrical grinding and centerless grinding), the commonly selected parameters are the cutting speed, the feed rate and the depth of cut. (3) In different processing conditions (grinding method, type of grinding wheel, material type of workpiece, and so on), roughness model has different form. At the same time, in those studies, the influence of the input parameters on the roughness of the workpiece is also different. Therefore, it is necessary to conduct experimental studies in each specific condition to build the surface roughness model of the part.

IV. CONCLUSIONS

Some conclusions drawn from this study are as follows:

1) Experimental studies to build a regression model showing the relationship between the surface roughness of the workpieces and the parameters of the machining process has been performed by many authors. However, in each specific processing condition, the regression model has different values.

2) The input parameters in published studies are usually the cutting parameters.

3) In each specific processing condition, in order to process the surface roughness of the workpiece to meet the requirements, experimental study can be carried out to build a surface roughness model with cutting parameters. The relationship will also help to determine the degree of influence of each parameter on the surface roughness, which is the basis for the control of the grinding process.

ACKNOWLEDGEMENTS

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