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A New Approach to Building a Surface Roughness Model While Grinding That Takes into Account the Elastic Modulus of Grinding Wheel and Workpiece Materials

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Abstract— *A study on surface roughness modeling of parts during grinding has been presented in this paper. By analyzing several previously published models, this study identified a model that has many advantages over other models. After identifying a model with many advantages, this study proceeds to develop and improve that model. Model development is carried out by considering two factors that greatly influence surface roughness during grinding, including the elastic modulus of the grinding wheel and the elastic modulus of the workpiece material. When applying the improved model to predict surface roughness, the results were compared with the actual value when using Al_2O_3 grinding wheels to grind C45 steel. The results show that the predicted surface roughness value is very close to the experimental results, the average deviation is only about 6.22%. This research opens up prospects for predicting the surface roughness of parts when grinding.*

Keywords— *Roughness model when grinding, grinding C45 steel, Al_2O_3 grinding wheel.*

I. Introduction

The impact of surface roughness on product performance and longevity is undeniable [1-4]. This is especially important when the part surface is finally processed by grinding [5, 6]. Therefore, evaluating the effectiveness of the grinding process often chooses surface roughness as one of the main criteria. However, studying surface roughness through experimental methods often requires a lot of time and cost, and the application effectiveness of experimental results is also limited [7, 8]. Therefore, many researchers have conducted research and developed models to predict surface roughness when grinding using different methods. In this article, the authors will perform an analysis to select a roughness prediction model with many advantages from several previously published models. The authors then researched to improve this model for predicting the surface roughness of parts when grinding.

To overcome the limitations mentioned above regarding experimental research methods, surface roughness models during grinding are developed based on theoretical analysis of the grinding process performed by some authors. The construction of these models does not depend on specific machining conditions, so they can be applied in a wider range.

A model to predict surface roughness when surface grinding has been built as in formula (1) [7].

$$R_a = \frac{1}{9\sqrt{3}}\left(\frac{v_w L}{v_s d_s^{1/2}}\right)^2 \quad (1)$$

In there:

v_w is the velocity of the workpiece.

v_s is the grinding wheel velocitiy.

L is the contact arc length between the grinding wheel and the machined surface

d_s is the grinding wheel diameter.

With the assumption that the cut mark of each abrasive grain left on the surface of the part is in the shape of a triangle, a roughness model has been built as formula (2) [8].

$$E(R_a) = 0.37\, E(h) \quad (2)$$

In there:

$E(R_a)$ is the expectation of surface roughness.

$E(h)$ is the expectation of undeformed chip thickness.

With the assumption that the cut mark of each abrasive grain left on the surface of the part is in the shape of a semicircle, a roughness model has been built as a formula (3) [9].

$$E(R_a) = 0.423\, E(h) \quad (3)$$

Also with the assumption that the cut mark of each abrasive grain left on the surface of the part is in the shape of a semicircle, another roughness model has been built as formula (4) [9].

$$E(R_a) = 0.471\, E(h) \quad (4)$$

In another study, also with the assumption that the cut mark of each abrasive grain left on the surface of the part is in the shape of a semicircle, another roughness model was built as formula (5) [10].

$$E(R_a) = 0.396\, E(h) \quad (5)$$

With the assumption that the cut mark left by each abrasive grain on the surface of the part is in the form of a part of a curved arc, a roughness model has been built as a formula (6) [11].

$$E(R_a) = 0.92\ E(h) \quad (6)$$

Snoeys et al [12], Kedrov [13] built a model (7) to predict surface roughness during grinding. In which $R_1$and $x_1$are coefficients that depend on machining conditions and must be determined by experimental methods.

$$R_a = R_1\left(\frac{v_w a}{v_s}\right)^{x_1} \quad (7)$$

Where: a is the depth of cut.

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Akram Saad and colleagues [14] built model (3) to predict surface roughness during grinding. In which R_2 and x_2 are coefficients that depend on machining conditions and must be determined by experimental methods.

$$R_a = R_2 s_d^{0.5}\, a_d^{0.25} \left(\frac{v_w a}{v_s}\right)^{x_2} \tag{8}$$

In there:

a_d is the dressing depth.

s_d is the feed rate when dressing.

We see that models (1) to (6) have been built based on theoretical methods of the cutting process, so they are widely applicable. However, these models do not consider many parameters that affect surface roughness such as parameters dressing, type of grinding wheel, type of workpiece material, etc.

For model (7) and model (8), although they are also built based on theoretical methods, to apply them, it is necessary to conduct experimental research to determine the value of the R_1 coefficients and R_2 with exponents x_1, x_2. However, both of these models do not consider many parameters that affect surface roughness. Therefore, the application of these two models to predict surface roughness also has many limitations.

Several surface roughness prediction models have been built by the authors based on specific machining conditions of machining material and grinding wheel type.

When grinding 4140 steel with a 38A60K5VBE grinding wheel, a model was built as in formula (9) [15].

$$R_a = 12.9 s_d^{0.54} a_d^{0.34} \left(\frac{v_w}{v_s}\right)^{0.38} \left(\frac{s_t}{b_s}\right)^{0.43} \tag{9}$$

In there:

s_t is the horizontal feed rate.

b_s is the width of the grinding wheel.

When grinding C45 steel with CBN grinding wheel brand HY-180x13x31.75-100, a model was built as in formula (10) [16].

$$R_a = 0.92 * 0.3574^{0.094} * h \tag{10}$$

In which: h is the undeformed chip thickness. Calculating the value of h can be learned in the study of Anne Venu Gopal and colleagues [1].

When grinding AISI 52100 steel with a 2A80K4VFMB grinding wheel, a model was built as in formula (11) [17, 18].

$R_a = 0.487\, T_{aV}^{0.3} \quad for \quad 0 < T_{av} < 0.254$

$R_a = 0.7866\, T_{aV}^{0.72} \quad for \quad 0.254 < T_{av} < 2.54$

Where:

$$T_{av} = 12.5 \times 10^3 \frac{d_g^{16/27}\, a_p^{19/27}}{d_e^{8/27}} \left(1 + \frac{a_d}{s_d}\right) s_d^{16/27} \left(\frac{v_w}{v_s}\right)^{16/27} \tag{11}$$

In there:

d_e is the equivalent grinding wheel diameter, $d_e = d_w * d_s/(d_s \pm d_w)$, the plus sign is used when external grinding and the minus sign is used when internal grinding.

d_w is the wokrpiece diameter.

d_g is the abrasive grain diameter, $d_g = 15.2/M$.

M is the granularity of the grinding wheel.

From the above models, it can be seen that when the roughness model is built based on specific machining conditions, the accuracy in predicting roughness will be close to reality. However, in the model number (9), only the type of grinding wheel is considered, without considering other parameters of the grinding wheel such as mudulus, adhesive, number of structures, grain dimensions, etc.

For model number (10), grinding wheel properties, parameters dressing, etc have not been considered. For the numerical model (11), many parameters such as parameters dressing and grain demision (through d_g value) are mentioned, but clearly, this model is only suitable for application in predicting stone grain density. Surface roughness when using 2A80K4VFMB stone to grind AISI 52100 steel.

When simulating the grinding process using the Genetic Programming method (GP), a model has been proposed according to formulas (12) to (15). This is a study based on the theoretical analysis of the grinding process [12].

$$R_a = \left(0.72+\frac{v_w}{v_s}\right)^{\frac{0.3\left(\frac{s_t}{b_s}\right)^{\left[10-a_d+\left(\frac{v_w}{v_s}\right)^{0.3^{\frac{\left(\frac{v_w}{v_s}-a_d+1\right)\left(\frac{s_t}{b_s}\right)^{0.847}}{1.39-(ad_e)^{0.2963}}}}\right]}}{\left[\left(\frac{v_w}{v_s}\right)^{0.3^{\frac{\left(\frac{s_t}{b_s}\right)^{0.847}}{10}}}\right]^{\left(\frac{v_w}{v_s}\right)r}}\left[\left(\frac{v_w}{v_s}\right)^{0.3^{0.3^{\left(\frac{\left(\frac{s_t}{b_z}\right)^{0.487}}{\left(\frac{s_t}{b_s}\right)^{0.237}}\right)}}}\right]^{0.487}} - \frac{2\left(\frac{v_w}{v_s}\right)}{\left[{s_d}^{0.3^{\left(\frac{\left(\frac{s_t}{b_s}\right)^{0.487}}{\left(\frac{\frac{s_t}{b_t}+s_d\frac{s_t}{b_s}+\frac{v_w}{v_s}}{s_d}\right)^{0.3}}\right)}}\right]^{0.487}} \tag{12}$$

In there:

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$$r = \frac{0.3^{\left(\frac{s_t}{b_s}\right)\left[10-a_d+\left(\frac{v_w}{v_s}\right)^{0.3^{0.3^{\left(\frac{\left(\frac{v_w}{v_s}-a_d+10\right)\left(\frac{s_t}{b_s}\right)^{0.487}}{1.3892-(a.d_e)^{0.2963}}\right)}}}\right]}}{\left[\left(\frac{v_w}{v_s}\right)^{0.3^{\frac{\left(\frac{s_t}{b_t}\right)^{0.487}}{10}}}\right]^{\left(\frac{v_w}{v_s}\right)^{(r_1)^{0.237\left(\frac{s_t}{b_s}\right)}}}} \quad (13)$$

With:

$$r_1 = (r_2)^{a_d\left[\frac{\left(\frac{v_w}{v_s}0.7037^{\frac{0.3^{0.487\left(\frac{s_t}{b_s}\right)^{0.487}}}{2(1.3892-(a.d_g)^{0.2963})}}\right)^{0.487}}{0.5926^{\left(\frac{s_t}{b_s}\right)^{0.1416}}}\right]} - 2\left(\frac{v_w}{v_s}\right)\left(\frac{v_w}{v_s}\right)^{\left(\frac{v_w}{v_s}-a_d+10\right)\left(\frac{s_t}{b_s}\right)^{0.237}} \quad (14)$$

With:

$$r_2 = \frac{\left(\frac{v_w}{v_s}\right)^{0.487*0.3^{\left(\frac{\frac{v_w}{v_s}}{\left(\frac{s_t}{b_s}\right)^{0.237}}\right)}}}{0.3^{\left(\frac{s_t}{b_s}\right)^{0.3\left(\frac{v_w}{v_s}-a_d+10\right)\left[\frac{\left(\frac{v_w}{v_s}\right)^{0.487*0.3^{\left(\frac{v_w}{v_s}\right)}}}{0.3^{\left(\frac{s_t}{b_s}\right)^{0.487 s_d}}}\right]}}} - \frac{2\frac{v_w}{v_s}}{\left[\left(\frac{S_t}{b_s}\right)^{0.237\frac{v_w}{v_s}}\right]^{0.487}} \quad (15)$$

Observing the formulas from (12) to (15) shows that this model considers many factors affecting surface roughness such as cutting velocity, workpiece velocity, cutting depth, and dressing depth, feed rate when using a grinding wheel, width of grinding wheel, grinding wheel diameter, part diameter, abrasive grain size, etc. This model shows many advantages compared to the previously presented models (from model (1) to model (11)). However, this model does not consider the characteristics of the machining material and grinding wheel, which are important factors affecting surface roughness. Therefore, to improve the accuracy of the surface roughness model (from equations 12 to 15), this study will consider the elastic modulus of the grinding wheel and the elastic modulus of the machined material. Based on that basis, the roughness model is proposed as formula (16), in which *Ra* is expressed according to formulas from (12) to (15).

$$R_{a-present} = \left(\frac{E_s}{E_w}\right)^n * R_a \quad (16)$$

In there:

E_w is the elastic modulus of the machined material.

E_s is the elastic modulus of the grinding wheel.

n - exponent, this coefficient depends on specific machining conditions.

1. Predict surface roughness when grinding

Use the surface roughness model by combining formulas from (12) to (16) to predict surface roughness when grinding C45 steel with CBN grinding wheels. For CBN grinding wheels, because the thickness of the stone layer is only a few millimeters, very small compared to the inner diameter of the aluminum disc, the elastic modulus of the grinding wheel can be considered equal to the modulus of the inner aluminum disc.

The experiments were carried out under the following conditions: using a surface grinder manufactured in Taiwan, the grinding wheel is CBN wheel, grinding wheel diameter is 240 (mm), stone granularity is 80, experimental materials are C45 steel, grinding wheel width is 15.6 (mm), cutting velocity is 32 (m/s), workpiece velocity is 10 (m/min), grinding depth is equal to 0.02 (mm), feed rate when dressing is equal to 120 (mm/min), the horizontal feed rate is equal to 6 (mm/stroke), the elastic

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modulus of CBN grinding wheel is equal to 70 (GPa), the elastic modulus of machined material equal to 200 (GPa).

Through several experiments, it was determined that a value of *n* equal to 0.011 will ensure that the predicted roughness value will be close to the experimental roughness value. Based on the calculation results, it is seen that the roughness value predicted by the roughness model (according to formulas (12) to (16)) is very close to the experimental roughness value. According to the calculated data, the average difference between the predicted value and the experimental value is only 6.22%. From there, it can be concluded that adding parameters on the elastic modulus of the machined material and the elastic modulus of the grinding wheel to the surface roughness model allows very accurate predictions compared to real results. experience.

II. CONCLUSION

This study inherited and developed a surface roughness model when grinding with many advantages. Expansion of the model by adding the elastic modulus of the grinding wheel and the elastic modulus of the workpiece material was carried out. Once developed, the model was used to predict surface roughness when grinding and compared with experimental results when grinding C45 steel with CBN grinding wheels. The study's results were very positive, with an average deviation between predicted and experimental results of only about 6.22%. Using this model to predict surface roughness reduces machine adjustment time and trial machining time, and improves the grinding process's efficiency.

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