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ORIGINAL ARTICLE

Modeling and analysis of grinding forces based on the single grit scratch

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Abstract Creating scratch by an abrasive grit is mostly investigated to enhance the finishing processes. The grinding process is such that a number of abrasives with a specific statistical distribution is engaged with the workpiece and performs the material removal. If we can consider the scratching and material removal processes for a single grit indicated on the grinding wheel as a smaller element, then the material removal process could be developed and extended for every engaged abrasive edge in the grinding. In this paper, a new analytical force model for grinding process is developed by modeling abrasive grits and their interaction with the workpiece individually. Grits are examined to determine their geometrical properties and distribution on the grinding wheel. Analytical equations for total normal and tangential force components are established. Especially, the model takes into account the microstructure of the grinding wheel given by the grain geometry and the grain density. Also, the effect of kinematical parameters and process inputs on the forces will be examined. The obtained results showed that the increasing in parameters such as the slope of abrasive grits on the surface of the grinding wheel and the number of active grits on the grinding zone lead to a reduction in forces. The validity of the model can be proved by comparison of experimental results. Modeling forces in the single grit scratch will be a key factor in accurate modeling of the grinding process, and the research findings provide important information for a better understanding of the process.

Keywords Modeling forces · Kinematical parameters · Topography of the grinding wheel · Single abrasive grit

Nomenclature

2a	Average distance between two successive grits
a_n	Depth of cut
b	Grinding width
C	Concentration factor
D_g	Grinding wheel diameter
d_g	Mean diameter of abrasive grits
F_t	Tangential grinding force component
F'_t	Specific tangential grinding force (N/mm)
F'_n	Specific normal grinding force (N/mm)
f_n	Normal force on the grit (N)
H_b	Workpiece surface hardness
H_s	Workpiece bulk hardness
h	Grit depth of cut
h_{eq}	Equivalent chip thickness
K	Wear coefficient of the workpiece (MPa^{-1})
k	Shear yield strength of the work
L	Distance between adjacent tracks
l	Dimensionless distance between tracks
l_c	Length of arc of cut
n_g	Number of active cutting points at contact
P	Grinding power
Q_w	Volumetric removal rate (mm^3/s)
q_g	Grinding speed ratio
u	Specific grinding energy
v_g	Grinding wheel surface speed
v_w	Workpiece speed
W	Wear volume
μ	Coefficient of friction
μ_0	Friction factor at the interface between grit and workpiece
α	Attack angle

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1 Introduction

Grinding is one of the main methods of precision machining. The grinding forces can be used as an indicator for monitoring the process. However, force values can be considered as the most essential ones since they lead us to the temperature and chatter vibration issues. The analytical modeling is of great importance in order to achieve a controllable process and predict the outputs. By using modeling, the quality of the grinding process can be enhanced. Also, the time and the cost of experimental evaluations can be reduced, and an accurate analysis of the grinding process can be achieved which is very difficult to obtain in practice. Based on the experimental results of studies on the relationship between the grinding force and abrasion plane area on the grinding wheel, the grinding force is composed of cutting force and plowing force which was proposed by Malkin and Cook [1]. Another grinding force model was established on the basis of the turning experiments, and normal chip formation force formula was proposed by Li and Fu [2].

Badger and Torrance [3] proposed two kinds of grinding force model, the first model is based on Challen and Oxley's 2-dimensional (2-D) plane-strain slip-line field theory and the second model is based on Williams and Xie's 3-dimensional (3-D) pyramid-shaped asperity model. These two models simulated the grit–workpiece interface to a rigid plastic contact and mechanical behavior in this kind of contact was influenced by the grit slope and interfacial coefficient of friction between the asperity and the worn material.

Another different grinding force model was proposed by Hecker [4]. According to this model, a Rayleigh probability density distribution was presented for the equivalent chip thickness. The mentioned distributions were affected by the process kinematics, material characteristics, and grinding wheel structure. Although modeling of grinding forces has been studied extensively by researchers, there are also several problems: grits which participate in grinding are geometrically irregular and randomly distributed. The abrasion of grinding wheel increases the temperature, strain, and strain rate in the grinding process [5]. The material strain rate in the grinding process is greater than the known normal machining process. This phenomenon is called size effect [6].

A consistent physical modeling of the grinding process must begin from the basic physics of the process given by the interaction of individual grinding grains with the workpiece. It must then be expanded to the behavior of the whole grinding wheel. Tecelli et al. [7] found that the chip removal mechanism changes during the single grit grinding. The experiments showed that the grit cutting ability changes with the deformation of the cutting edge. Grits that only have a single cutting edge are more efficient.

Regarding the recent modeling, models from Tang et al. [8] and Durgumahnti et al. [9] can be mentioned. A new mathematical model of grinding forces is developed for flat grinding in their studies. These modeling solutions have been developed based on the cutting mechanic.

Kinematical simulation of the grinding process was first introduced by Warnecke and Zitt [10]. This simulation is capable of calculating chip parameters such as equivalent chip thickness or non-deformed chip cutting section area in each active single grit on the grinding wheel surface. This is mainly developed and utilized to optimize the grinding tool. Williams and Xie [11, 12] were able to overcome the limitation of this model by considering the abrasion, cutting, and plowing within the deformation area, such that according to the new model, the cutting rate rises with the increase of attack angle (the slope of the abrasive grits on the surface of the grinding wheel or abrasive sharpness which is shown by α angle in Fig. 1) and decrease of coefficient of friction. Based on this work, Azizi et al. [13] proposed a model for predicting the specific grinding energy. In their research, the grinding process was modeled using abrasive single grit scratch. The novelty of their research was investigating the effect of the grinding wheel surface topography on the specific grinding energy. One of the most highlighted findings was that the attack angles of abrasive grits have more effect on consumed grinding energy than the amount of grits number in the grinding area. In the presented study, grinding forces are modeled based on the previous work [13]. Using this approach, the grits of a grinding wheel can be represented as hard pyramids. Hence, the forces on a single grit can be calculated from the workpiece material properties, the grinding wheel surface parameters, and the grinding process parameters. Then, the model is expanded for all active grits of grinding wheel in the grinding zone. Finally, using empirical tests, validity of the modeling is then studied and analyzed.

2 Grinding force model

This section deals with the modeling of forces as an indicator for assessing the grinding process. To this end, single grit forces are modeled and influential parameter on the grinding forces are studied. First, using the model obtained for the specific energy in previous work [13] and the model obtained for frictional factor (ratio of tangential to normal force μ) and grits abrasion factor (K) by Williams and Xie [11, 12], the tangential and the normal forces will be simulated. Using the obtained model, the effects of process input parameters on the grinding forces could be examined. Then, the simulation results are compared with experimental results.

The grinding process and material removal process consumed power and energy. The grinding forces in the flat and cylindrical grinding processes consist of two components: tangential and normal.

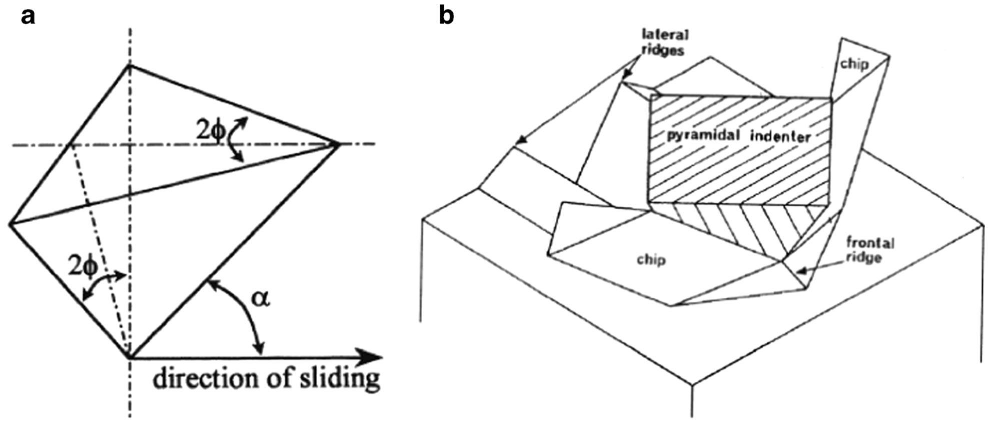

Fig. 1 **a** The 3-D abrasive grit model. **b** Simultaneous cutting and plowing by an abrasive grit [3]

It is shown that the grinding power is proportional to the grinding force components [14]:

$$P = F_{\mathrm{t}}(v_{\mathrm{g}} \pm v_{\mathrm{w}}) \tag{1}$$

where P is the grinding power, F_{t} is the tangential grinding force, and v_{g} and v_{w} are simultaneously grinding wheel and workpiece peripheral velocity. During the up-grinding, due to the opposite direction of the velocities of the grinding wheel and the workpiece, the positive sign is used and in the opposite case, the negative sign is used for the down-grinding. Since the workpiece speed is negligible compared to the speed of the grinding wheel, therefore the above equation can be simplified as follows:

$$P = F_{\mathrm{t}} v_{\mathrm{g}} \tag{2}$$

Equation (2) can be used for most of the grinding processes regardless of the power consumption for the traverse and downward motion of the grinding tool.

Material removal rate (Q_{w}) can be expressed as the production of the specific rate of removed chips (Q'_{w}) multiplied by the width of grinding wheel (b):

$$Q_{\mathrm{w}} = Q'_{\mathrm{w}}.b = a_{\mathrm{n}} b v_{\mathrm{w}} \tag{3}$$

where a_{n} is depth of cut. The specific energy is the amount of consumed energy per unit volume of removed material which can be defined as follows:

$$u = \frac{P}{Q_{\mathrm{w}}} = \frac{F_{\mathrm{t}} v_{\mathrm{g}}}{Q'_{\mathrm{w}}.b} \tag{4}$$

The grinding-specific energy model presented in the previous paper [13] is based on a 3-D model for the interaction of a single hard pyramid-shaped grit in repeated sliding contact with the workpiece surface. Therefore, the model is expanded for all of the active grits in the grinding zone. Inputs to this model are the material properties of the workpiece, grinding operation parameters, and the grinding wheel topography parameters. In particular, the model indicates two key topographical parameters: the number of active grits per unit area and their slope. It means that by this model, the grinding forces are related to the grinding wheel surface parameters.

According to equations (3) and (4), specific grinding energy can be written as:

$$u = \frac{F_{\mathrm{t}} v_{\mathrm{g}}}{a_{\mathrm{n}} b v_{\mathrm{w}}} \tag{5}$$

$\frac{F_{\mathrm{t}}}{b_{\mathrm{n}}}$ is the specific tangential grinding force and the quantity $\frac{a_{\mathrm{n}} v_{\mathrm{w}}}{v_{\mathrm{g}}}$ is called the equivalent chip thickness (h_{eq}) [14].

$$F'_{\mathrm{t}} = \frac{F_{\mathrm{t}}}{b_{\mathrm{n}}} \tag{6}$$

$$h_{\mathrm{eq}} = \frac{a_{\mathrm{n}} v_{\mathrm{w}}}{v_{\mathrm{g}}} \tag{7}$$

By combination the equations (5), (6), and (7), specific grinding energy can be rewritten as:

$$u = \frac{F'_{\mathrm{t}}}{h_{\mathrm{eq}}} \tag{8}$$

The tangential grinding force can be expressed as the product of specific energy and equivalent chip thickness which is changed continuously with the cutting conditions. Equivalent chip thickness is a measure of the depth of penetration of the abrasive grains in to the workpiece. Here, it is used to investigate the effect of kinematical input parameters such as depth of cut (a_{n}) and grinding speed ratio between grinding wheel surface speed and workpiece speed ($\frac{v_{\mathrm{g}}}{v_{\mathrm{w}}}$).

The 3-D abrasion model used to predict grinding forces as a function of grinding wheel topography uses the pyramid-shaped grit as shown in the Fig. 1 [3].

For a given attack angle of abrasive grit α and friction factor at the interface between the grit and workpiece μ_0, the regime of contact (rubbing, plowing, or cutting) can be determined. For each regime, the horizontal force, the wear coefficient of the workpiece (K), and the coefficient of friction (μ) can be calculated. They are related to the friction factor (μ_0), the ratio of bulk to surface hardness of the workpiece $\frac{H_b}{H_s}$, and the dimensionless distance between tracks (l). The equations for μ and K and the criteria for which contact regime is present are reported in sliding a hard rough surface against a soft surface [11, 12].

$$\mu = \left(\frac{2}{\pi}\right)^{0.5}\frac{\tan\alpha}{l^{0.25}}\left(1-\mu_0\left[1+\frac{\pi}{4\tan^2\alpha}\right]^{0.5}\right) \tag{9}$$

$$K = 0.003\frac{\tan^3\alpha}{\mu_0 k l^{0.5}}\sqrt{\frac{H_b}{H_s}} \tag{10}$$

Using this approach and the definition of K [12]:

$$K = \frac{W}{f_n L} \tag{11}$$

f_n is normal force on the single grit and L is the distance between adjacent tracks. W is the wear volume for the single grit [12]:

$$W = \frac{h_{eq} L l_c}{n_g} \tag{12}$$

where l_c is the length of arc of cut and n_g is the number of cutting points at contact. By multiplying the linear density of the amount of active grits ($\frac{n_g}{l_c}$) with the normal force on a single grit (f_n), the amount of cumulative specific normal force will be achieved. Thus, specific normal force can be written as:

$$F_n' = \frac{n_g f_n}{l_c} = \frac{h_{eq}}{K} \tag{13}$$

Noting that cumulative specific tangential grinding force

$$F_t' = \mu F_n' \tag{14}$$

Then:

$$F_t' = \mu\frac{h_{eq}}{K} \tag{15}$$

By combining equations (15), (13), (10), and (9):

$$F_t' = 266\frac{a_n v_w}{v_g}\frac{\mu_0 k l^{0.25}}{\tan^2\alpha\sqrt{\frac{H_b}{H_s}}}\left\{1+\mu_0\left(1+\frac{\pi}{4\tan^2\alpha}\right)^{0.5}\right\} \tag{16}$$

$$F_n' = \frac{a_n v_w}{v_g}\frac{1}{0.003\frac{\tan^3\alpha}{\mu_0 k l^{0.5}}\sqrt{\frac{H_b}{H_s}}} \tag{17}$$

It is still necessary to define the dimensionless distance between tracks (l), for calculation of grinding forces. l is the relative overlap (overlap/scratch width) of successive grinding scratch [11]. According to Fig. 2, this is given as:

$$l = \frac{L}{h\tan\alpha} \tag{18}$$

The distance between adjacent tracks created by two successive active points is approximated by equation (19). This is in accordance with the number of active cutting points at contact calculated

$$L = \frac{l_c}{n_g} \tag{19}$$

$\frac{n_g}{l_c}$ is the linear density of active grits per unit length and from wheel-work kinematics [14]:

$$l_c = \sqrt{D_g a_n} \tag{20}$$

where D_g is the grinding wheel diameter.

h is the grit depth of the cut and from the wheel-work relations is further computed using the following equation [14]:

$$h = 2a q_g\sqrt{\frac{a_n}{D_g}} \tag{21}$$

q_g is the grinding speed ratio between the grinding wheel surface speed and workpiece speed. *2*a is the average distance between two successive grits on the grinding wheel surface. By using a CBN grinding wheel to the grinding workpiece surface, this can be calculated as [15]:

$$2a = \left(\frac{0.74\pi}{C}\right)^{\frac{1}{3}} d_g \tag{22}$$

where C is concentration factor, which indicates the amount of abrasives contained in the grinding wheel. This means that 2a depends on the characteristic grain size d_g and the concentration factor. According to the last two equations and the grinding wheel used, the grit depth of the cut is given by:

$$h = 2.1 d_g q_g\sqrt{\frac{a_n}{D_g}} \tag{23}$$

Thus:

$$l = \frac{D_g\tan\alpha}{2.1 d_g q_g n_g} \tag{24}$$

By inserting the equations (24) in equations (16) and (17), a model for predicting the tangential and normal grinding force is achieved.

$$F_t' = 266\frac{a_n v_w}{v_g}\mu_0 k\left(\frac{D_g\tan\alpha}{2.1 d_g q_g n_g}\right)^{0.25}\left(\tan^2\alpha\sqrt{\frac{H_b}{H_s}}\right)^{-1}\left\{1+\mu_0\left(1+\frac{\pi}{4\tan^2\alpha}\right)^{0.5}\right\} \tag{25}$$

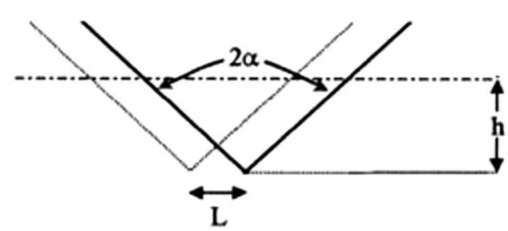

Fig. 2 Distance between adjacent tracks

Table 1 Summary of setup of parameters for the dressing and grinding system

Machine	
Hauni-Blohm HFS 204	Model
4000 rpm	Max. spindle speed
10 kW	Spindle power
Grinding system	
1A1 200 10 3 51 B91 Vit. N V100	Grinding wheel
13, 15, 18, 20, 25, 30 m/s	Wheel speed
0.6, 0.1, 0.15, 0.2, 0.25 m/s	Wokpiece speed
2, 4, 6, 8, 10, 12 um	Depth of cut
Inconel 738	Workpiece
3 % emulsion, 5.4 lit/min	Coolant
Dressing system	
50 mm	Cup diameter
5 mm	Width of diamond rim
3 mm	Depth of diamond rim
−0.6, −0.4, −0.2, +0.2, +0.4, +0.6, +0.8	Dressing speed ratio
3, 5, 7 um	Depth of dressing
50, 66, 100, 200	Overlap factor
Stepper motor	Cross-feed driver

$$F_n^{'} = \frac{a_n v_w}{v_g}\left(0.003\frac{\tan^3\alpha}{\mu_0 k\left(\frac{D_g \tan\alpha}{2.1 d_g q_g n_g}\right)^{0.5}}\sqrt{\frac{H_b}{H_s}}\right)^{-1} \quad (26)$$

The grinding forces derived through equations (25) and (26) gives a maximum value that describe the consolidated values of forces induced due to grinding mechanisms such as rubbing, plowing, and cutting. In comparison with previous models, the novelty and uniqueness of the presented model is investigating the effect of the number of active grits on the grinding wheel surface and their sharpness on the grinding forces. They are indicated by n_g and tan α in the presented model.

According to equations (25) and (26), grinding forces are effected by:

– Workpiece parameters, such as shear yield strength of the work surface k, the microhardness of the work surface, the bulk hardness of the workpiece (in this study, for simplicity, the value of $\sqrt{\frac{H_b}{H_s}}$ is approximated to be close to unity), and the coefficient of the friction
– Grinding parameters, such as the speed ratio between the grinding wheel surface speed and workpiece speed and grinding depth of cut
– The grinding wheel topography parameters, number of active grits at contact (ng), and slope of the active grits (tan α)

3 Experimental work

A group of experiments were carried out using HAUNY BLOHM HFS204 surface grinder, and the grinding wheel used for the experimentation was a medium grade vitrified CBN wheel with a grain size number of B91. The forces were measured using a 3-axis piezoelectric Kistler 9255A dynamometer. A measured tangential and normal grinding force sample is shown in Fig. 3. The workpiece used was super alloy (Inconel 738). The experimental conditions are listed in Table 1. To investigate the grinding wheel topography after dressing, replication technique along with Talysurf CCI instrument were used. After dressing, the topography of the wheel surface was recorded. By variation dressing conditions from soft through coarse dressing, the grinding wheel topography will change. Therefore, the amount of active grits and their sharpness will also change (see Fig. 4). Then, the record was analyzed to provide data for grit density and slope. For the medium porosity CBN grinding wheel (B91) which was used in this investigation, the grits with the height of more than 11 μm were considered as active grits [16]. The grit slope was obtained by differentiating the profile.

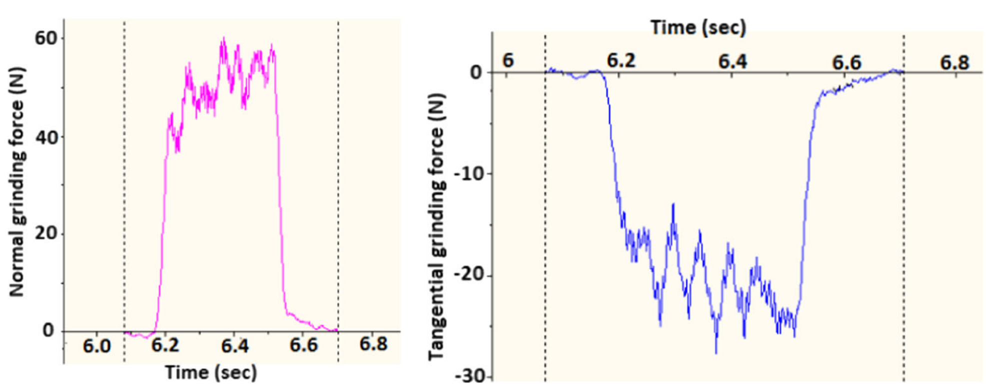

Fig. 3 A measured normal and tangential grinding force sample

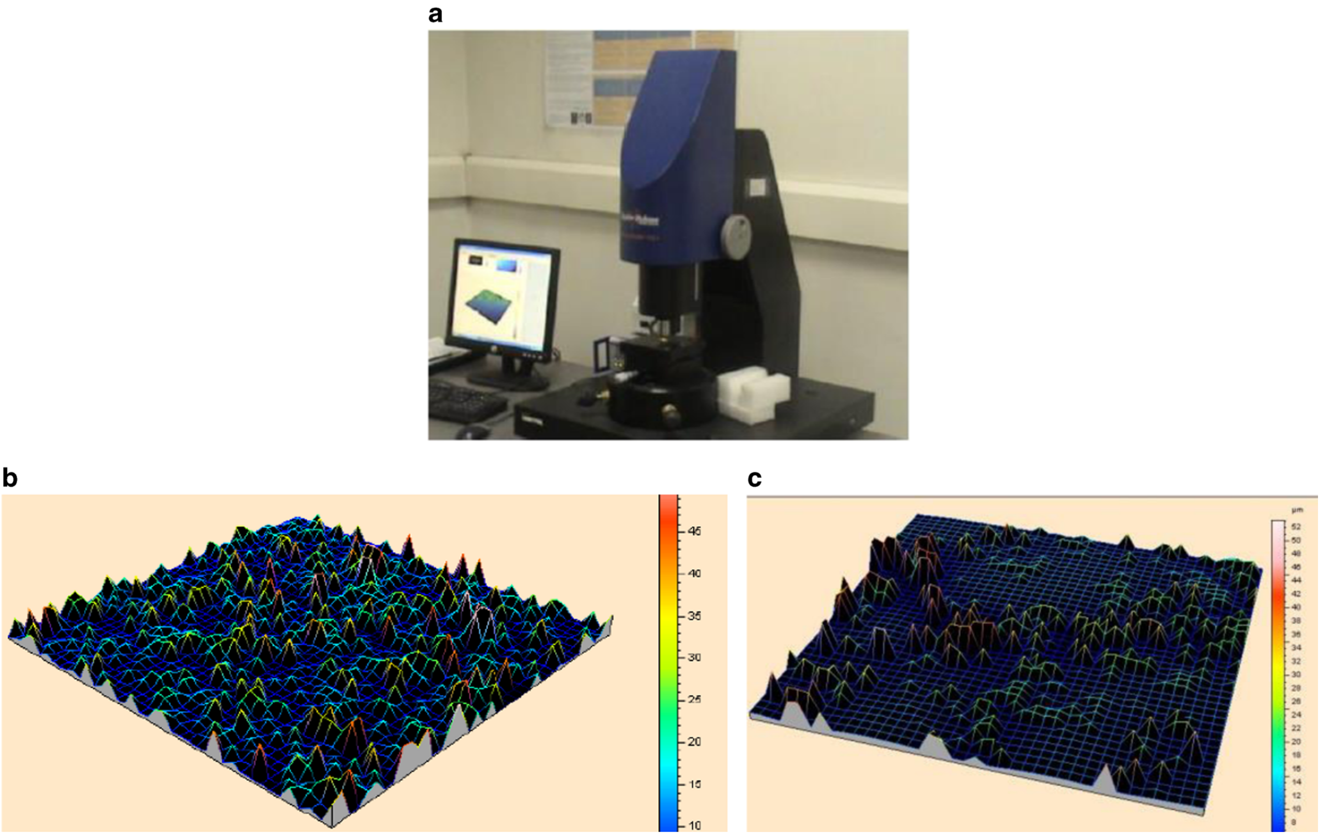

Fig. 4 **a** Talysurf CCI instrument used in this investigation along with a wheel imprint sample for determining the grains distribution after **b** coarse dressing and **c** soft dressing

4 Results and discussions

4.1 The effect of grinding wheel topography on the grinding forces

Variation of two key parameters on the grinding force from the model and experimental results is shown in Figs. 5 and 6. It can be clearly seen that the results of the proposed model have the same trend with those experimentally obtained. In general, grinding forces are found to decrease as the number of cutting points and their slope increase. The inverse relationship between grinding force and grinding wheel surface parameters is often referred to as the "size effect" [6]. Such large grinding

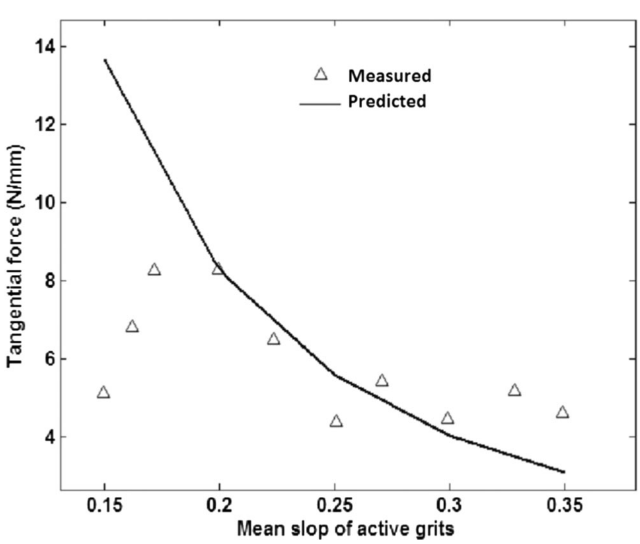

Fig. 5 The effect of the slope of the abrasive grits on the tangential force

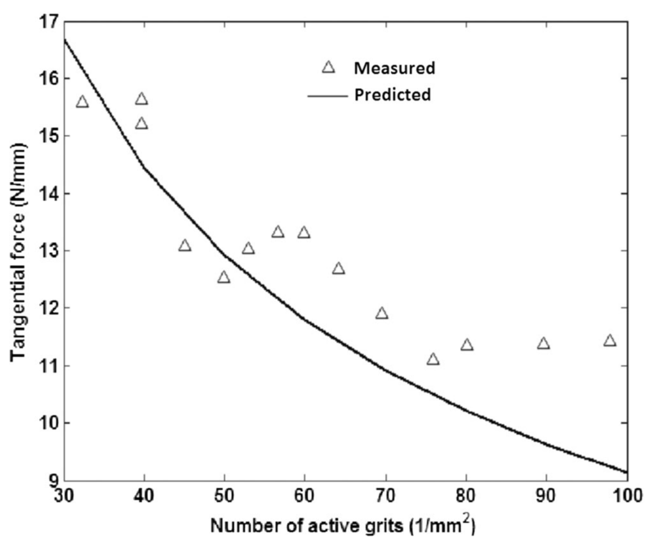

Fig. 6 The effect of number of active abrasive grits on the tangential force

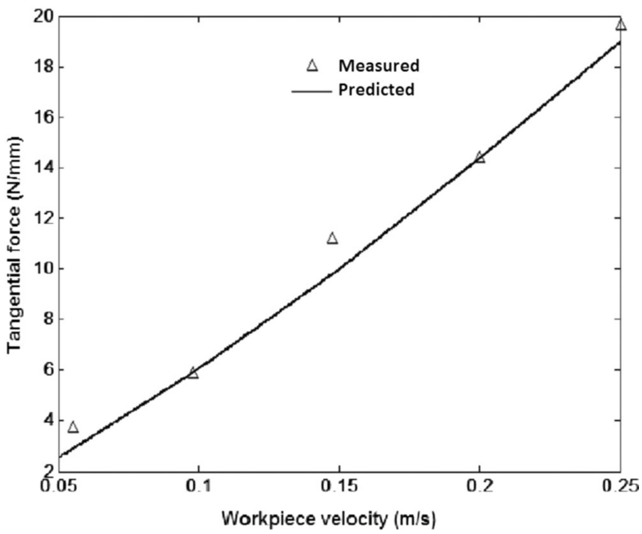

Fig. 7 The effect of workpiece velocity on the tangential force

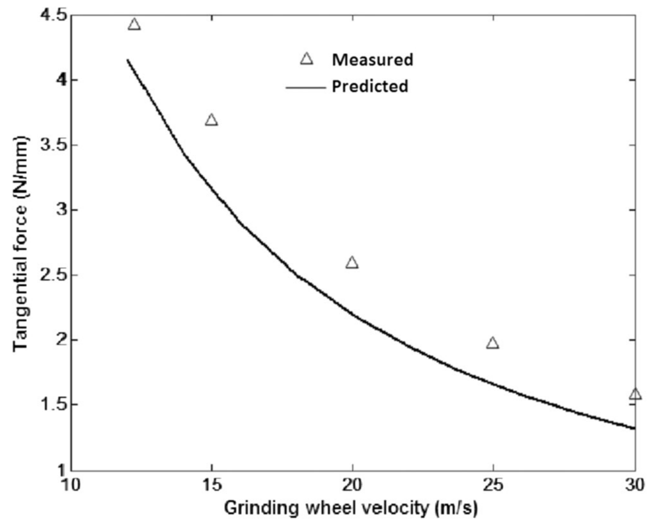

Fig. 9 The effect of grinding wheel velocity on the tangential force

force in grinding would indicate that the energy expenditure is mainly associated with ductile flow (plowing). Actually, material removal takes place by the cutting action. Furthermore, the grinding force increases as the number of cutting points and their sharpness decreases. This is due to an increased tendency for ductile flow rather than cutting as the abrasive grits interact with the workpiece. Grinding with sharp grits causes an increase in the cutting action and there is no wasted energy due to plowing. It can be seen that the decrease rate of the grinding force against the slope of active grits is higher than that against the number of active grits. This means, changing the cutting point's sharpness has a more powerful effect on grinding forces. In order to have sharp grits, rough dressing is required. According to the presented cup dressing experimental results, dressing with speed ratio greater than +0.2 and low overlap ratio is recommended. For selected operational parameters in this investigation, the variation of slope through 0.2 to 0.25 has greater effect on grinding force than through 0.3 to 0.35. This may account for changing metal removal mechanism from plowing to cutting action.

4.2 Workpiece velocity

The workpiece velocity is very low compared to the cutting velocity of the grinding wheel, in a way that the ratio of cutting velocity to workpiece velocity can vary from 100 to 200 for flat grinding. The effect of workpiece velocity on the grinding forces is shown in Figs. 7 and 8. According to the figures, increasing the workpiece velocity leads to increase in grinding forces. This is due to an increase in equivalent chip thickness during the material removal process.

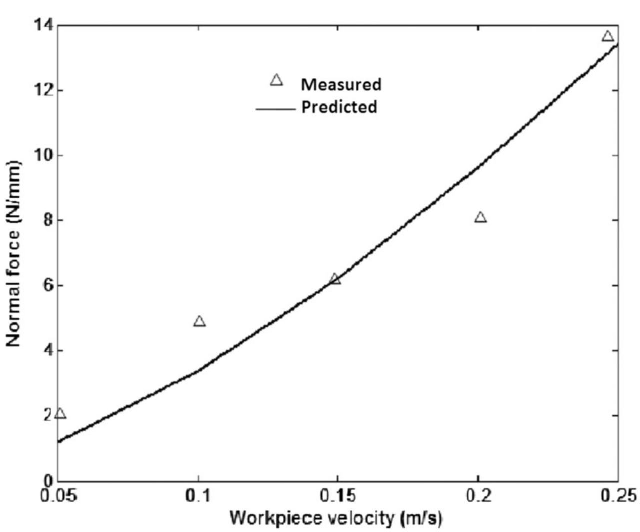

Fig. 8 The effect of workpiece velocity on the normal force

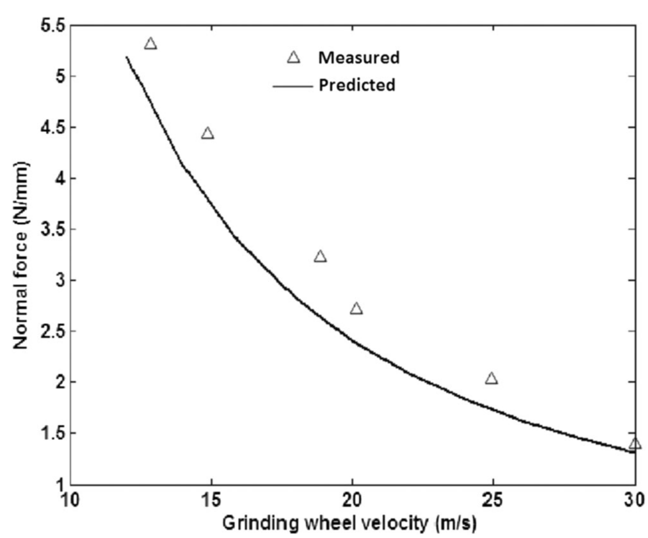

Fig. 10 The effect of grinding wheel velocity on the normal force

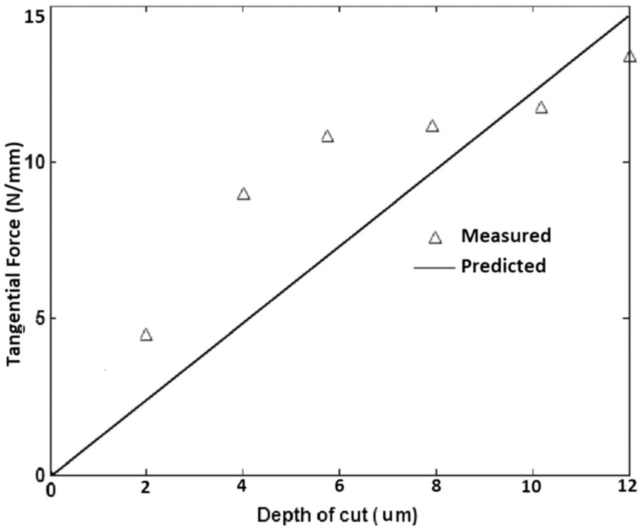

Fig. 11 The effect of depth of cut on the tangential grinding force

4.3 Grinding wheel velocity

It can be seen in Figs. 9 and 10 that an increase in grinding wheel velocity leads to a decrease in tangential and normal forces. All other parameters are considered as constants, and only the effects of grinding wheel velocity on the grinding forces are investigated. As mentioned previously, the increase in the grinding wheel velocity leads to a decrease in chip thickness. The reduction in chip thickness will in turn lead to a decrease in the material removal forces. This is in contrast with the effect of the increase in the workpiece velocity.

4.4 Depth of cut

As could be seen in Figs. 11 and 12, as the depth of cut increases, tangential and normal grinding forces increase as well. All other parameters are considered as constant, and only the effect of depth of cut on the grinding forces are investigated. This results are not surprising, because the increase in the depth of cut leads to a more severe material removal condition and consequently an increase in the grinding force.

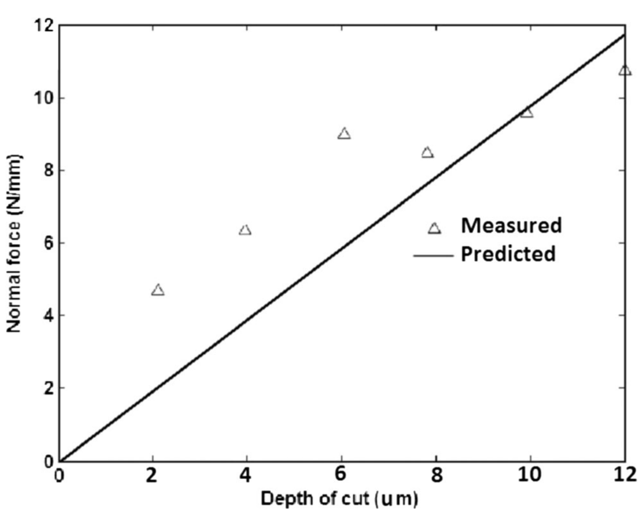

Fig. 12 The effect of depth of cut on the normal grinding force

5 Conclusion

A new model for grinding force was presented in this study, and the influence of grinding process parameters, including kinematical parameters, and particularly the grinding wheel surface characteristics such as the number of active grits in cutting area and their sharpness was examined. Simulation and computational results corresponded well with the experimental measurements, which prove the correctness and effectiveness of the proposed model. Results reveal that grinding forces inversely decreases when the number of cutting points and their slope increases. Forces diminish progressively regardless of whether the number of cutting points or their slope is further increased. This could be attributed to an increased tendency for cutting action and chip formation rather than plowing and sliding as the abrasive grains interact with the workpiece. The slope of cutting points has greater effect on the grinding forces than the number of active cutting points. This new grinding forces model could be reliably used to predict grinding forces and provide a specific theoretical basis for research on grinding forces. The way it used to drive model in this paper could also be established for simulating the other machining process which was conducted by scratching a hard tool with a soft work.

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