Performance evaluation of a grinding wheel using aggressiveness number

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ABSTRACT

KEYWORDS

Line Aggressiveness Number,
Plunge Surface Grinding,
Specific Energy,
Surface Roughness.

Under high temperature and stress, the wheel-workpiece contact zone experiences plastic deformation followed by adhesion at the junctions, resulting in the development of micro welds. As a result, the grits lose their sharpness, making the grinding wheel dull and raising both the grinding forces and temperature. Previous studies have suggested numerous ways of increasing grinding efficacy. The present study introduces a novel method to map the specific energy and surface roughness using a dimensionless entity known as the aggressiveness number. The surface grinding operation of medium carbon steel was performed using a vitrified bonded alumina wheel (A60K5V) under dry condition for varied grinding parameters. The corresponding grinding forces were measured to calculate the specific energy consumption of the process. Afterword, the variation of surface roughness values with process parameters has also been calculated. The verification results revealed that specific energy consumption was inversely proportional to aggressiveness number, whereas the relationship between surface roughness and aggressiveness number was non-linear. The findings of this study are likely to assist machine operators in selecting the appropriate parameters required to enhance surface finish.

1. Introduction

Grinding is a stochastic process wherein wide range of activities take place at tool-work interaction zone. The aggressiveness number can help in unifying various aspects like kinematics and geometry of the grinding wheel to provide a relationship between input parameters so that the output of the grinding operation is predicted in advance. And hence it reduces lots of effort in repeated experimentation for different parameters each time. Little has been done in this area till date.

The use of a dimensionless number is usually done to study a fundamental process. In the year 2008, for the first time, a new term 'Aggressiveness number' was coined (Badger, 2008). This term is a collection of wheel speed, table feed and depth of cut. The objective behind establishing such a term was to study the effect of multiple grinding process outputs through this dimensionless number. The output variables in the grinding process are not only dependent on a single input parameter instead on the whole set of input parameters such as speed of the wheel, table feed and depth of cut. Hence, using aggressiveness number to study the grinding process can help in understanding of the combined effect of all process inputs on output of the process as schematically shown in Fig. 1.

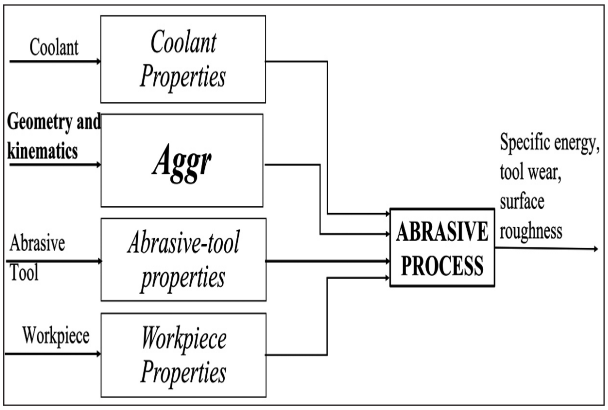

Fig. 1. Line aggressiveness number has combined geometry and kinematics into one dimensionless number (Badger, 2008).

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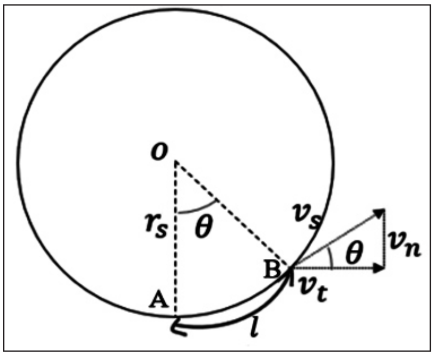


Fig. 2. Relative velocity vector and its component at the contact surface.

Aggressiveness number is defined as the ratio of normal to the tangential relative velocity vector. Mathematically, it is the angle (θ) at which the abrasive grits of a grinding wheel are entering the workpiece surface as shown in equation (1) and showcased in Fig. 2. In 2021, its relation with specific energy was successfully established for external cylindrical grinding operation. One such approach used by operators while manufacturing of a metal to increase material removal rate they go for increasing depth of cut. And to compensate the increased surface roughness higher wheel speed is chosen. Otherwise, the surface produced will be rougher surface hence more amount of time has to be spent to get the desired surface finish.

$$Aggr^{*} = \frac{v_n}{v_t} = \frac{\vec{v}\cdot\vec{n}}{\sqrt{\vec{v}\cdot\vec{v}-(\vec{v}\cdot\vec{n})^2}} \qquad ....(1)$$

This concept can be extended to the whole contact length to get an average point aggressiveness number for the whole contact, which is termed as “line aggressiveness number”.

$$Aggr' = \frac{1}{l_C}\int_{l_C} Agg\gamma^{*}\,\mathrm{d}l_C \qquad ....(2)$$

In the last two-three decades, various methods of modelling a process have been developed by various scientists across the globe. They are the physical process model (which can be defined by the numerical module, analytical method), empirical process model (which uses an artificial neural net model, regression analysis), and heuristic process model (rule-based model). All these modelling processes are very well explained by Brinksmeier et. al (2006). Shinozaki et al., (n.d) conducted tests on a vitrified bonded alumina wheel grinding wheel to find out the relation between bond strength and bond content in the wheel. They developed a relationship ship between the manufacturing condition of the vitrified bonded alumina wheel and its properties. Adibi et al., (2013) tried to find out the effect of input parameters such as depth of cut, wheel velocity and feed rate on the loading of the wheel. Hence, A theoretical model is presented by them based on adhesive wear which accommodates wheel topography, material specification and cutting parameters. It shows that the wheel loading percentage increases with increasing depth of cut. But no such relation is developed for the grinding process which helps to determine the grinding wheel life based on operating parameters. Malkin & Guo (2008) presented an analytical model to determine operating parameters where the grinding tool life is limited by the burning of the workpiece. The analytical equation developed consists of specific energy in terms of wear flat area (which is a function of the fraction of the tool in contact with the workpiece) and operating parameters. At low-down feed, more material removal will occur at a larger wheel velocity. Increasing the depth of cut will increase the fraction of the tool in contact with the workpiece and hence more chances of workpiece burn may result. Setti, et al., (2017) in their research found out the importance of uncut chip thickness, depth of cut and number of active grit count. And found out that cutting edges count, and uncut chip thickness are important parameters to determine the output parameters. A stochastic model is developed to find out the number of active grit participating in the grinding process. As depth cut increases the protrusion of the grit into the workpiece increases so number of grits engaged in the grinding operation also increases. The number of grit counts is smaller for small depth of cut, hard material, and small grit size. A simulation is developed by Darafon et al., 2013 to determine uncut chip thickness, contact length, and surface finish which has incorporated the effect of a varying number of active grit counts and verified the model with the experimental values of length of contact, surface roughness and uncut chip thickness. Drazumeric et al., (2020) and Badger et. al. (2021) did some experimental work for cylindrical grinding to find out the relation between aggressiveness number with various kinematics and geometric aspects of the wheel on grinding of a workpiece. This study was mainly tries to establish a dimensionless scalar quantity which is termed as aggressiveness number and develop a relationship between specific energy for cylindrical grinding. They found out that specific energy is inversely proportional to aggressiveness number and a general trend of larger aggressiveness number gives a rougher surface is observed.

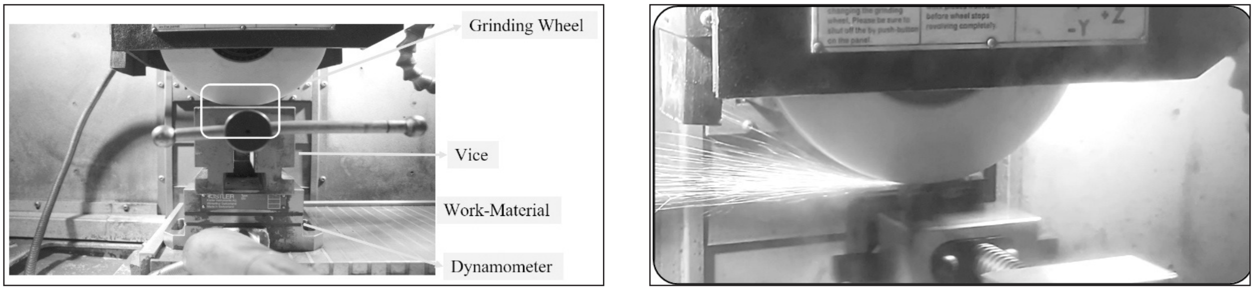


Fig. 3. Experimental setup used for carrying out grinding experiments and grinding wheel-workpiece interaction.

From the prior literature, it can be seen that most of the research on surface grinding investigated the machining responses, such as surface roughness or specific energy, with respect to one input parameter. The use of the aggressiveness number is constrained when analysing the overall effect of all grinding parameters. The performance assessment of the grinding wheel using the aggressiveness number is therefore the focus of the current investigation. In this regard, medium carbon steel samples were ground using an alumina wheel (A60K5V) with varied speed, feed, and depth of cut. Afterwards, cutting forces, specific energy, surface roughness, and chip morphology were observed throughout the grinding process. Finally, the relationship between aggressiveness number and surface roughness was established for the contemporary surface grinding process.

2. Experimental Details

To start with, alumina grinding wheels of A60K5V type were used for conducting the experimental work. The work material chosen for this study is a medium-carbon steel substrate. All grinding experiments were conducted under dry environment conditions in plunge surface grinding mode. The diameter of the grinding wheel used was 200 mm. A surface grinding machine of Make: Chevalier and model: smart B818III was used for the experiment as shown in Fig. 3 as well as wheel workpiece interaction is shown. To measure the grinding forces, a high-resolution dynamometer was used that was placed on top of a magnetic bed of the machine. A Kistler–9257B dynamometer was used for recording the normal and tangential grinding forces. The dynamometer was in-turn connected to a charge amplifier. The data generated during the grinding process were post-processed using Dynoware software. One of the objectives of the present study is to observe the morphology of chips generated during the grinding process. In this regard, a specialized setup was used for collecting the chips during the grinding operation. The scanning electron microscope was used for observing the morphology of the grits present on the periphery of the grinding wheel, for which a special technique was adopted for the preparation of the sample. To calculate the material removal rate (MRR), the weight of the sample was measured using AND GR-200 weighing machine both before and after the grinding operation. Surface roughness was measured using Taylor Hobson-Form Talysurf which is a 2D contact type surface profilometer. The cut-off length for measuring the surface roughness is taken to be 0.25 mm and the length of measurement was 5 mm. The scanning speed was 1 mm/s. The force results obtained using the dynamometer were used for calculating the specific energy and its variation was plotted w.r.t change in aggressiveness number. Different line aggressiveness number were obtained by changing input parameters (speed ratio, radial infeed, radius of wheel, etc.).

Table 1
Chemical complosition of work materials.
(http://Azom.com, 2020)

P	C	Mn	S	Fe
0.04%	0.28-0.34%	0.6-0.9%	0.05%	Balance

2.1. Selection of work material and grinding wheel

The work material used in the experiments was medium carbon steel AISI-1030 as it is preferable for conventional grinding operation and due to its easy availability and vast application in industries. These materials are known to be compatible with vitrified bonded Alumina wheel. The composition of the AISI-1030 steel is shown in Table 1. Fig. 4. depicts the grit morphology of these kinds of wheels. The dimension of the samples taken is 50x40x10 mm. The combination of the process parameters is taken from the details given in Table 2.

For the calculation of grit density, the Image was taken by SEM. The 1 mm^2 cross-section area was

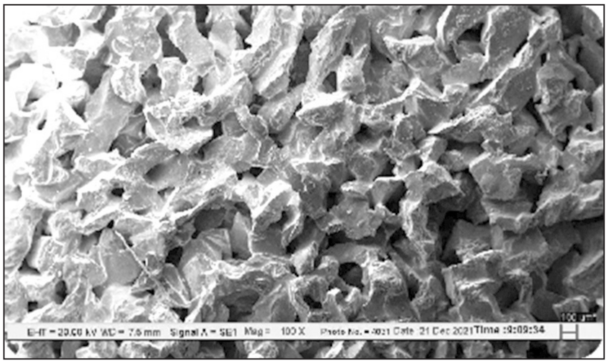


Fig. 4. SEM image of the grinding wheel.

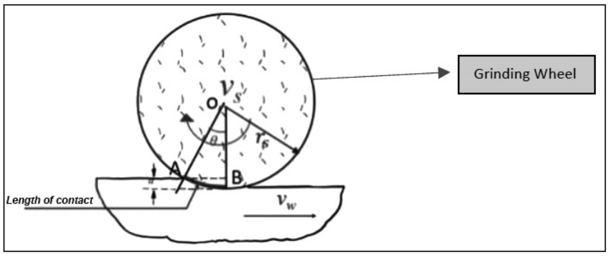


Fig. 5. Surface grinding process with geometry and kinematics.

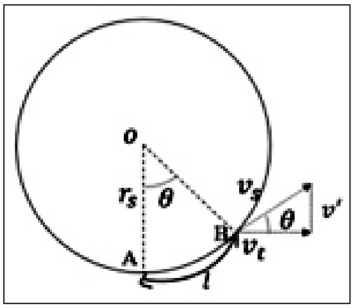


Fig. 6. Tool contact at a point B where contact length is /.

taken to count the grits available in that area. Using thatinformation, we can calculate the grit density or no. of grits available in 1 mm^2 area. This helps to calculate the uncut chip thickness value. The value of c (number of abrasives per unit area or grit concentration) is calculated from the SEM image of the wheel by Examining the number of grits in a 1mm^2 cross sectional area on doing the same the c value comes out to be 11 grit/mm^2.

3. Derivation of Analytical Expression

3.1. Length of contact

The schematic of the grinding wheel and the workpiece surface in up grinding mode is shown in Fig.5. Assumptions made while deriving the length of contact: a) deformation of workpiece and tool is neglected b) θ is very small.

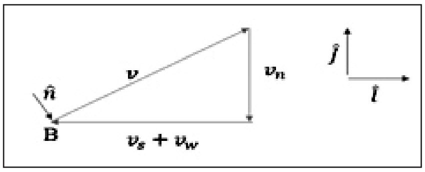


Fig. 7. Resultant relative velocity vector at contact point B between the workpiece and wheel.

Table 2
Experimental results.

Work Material	AISI-1030MediumCarbonSteel
Wheel	Vitrified Bonded Alumina
Type of operation	Plunge Surface Up Grinding
Wheel Speed	15m/s,20m/s,25m/s
Table Speed	3,6,9m/min
Depth of cut	5,7,10micron
Wheel Diameter	200 mm
Wheel Width	13 mm
Grinding Environment	Dry

$$l_c = \sqrt{2ar_s} \qquad \text{....................(3)}$$

$$\vec{v} = (v_s + v_\omega)\hat{\imath} + v'\hat{\jmath} \qquad \text{....................(4)}$$

$$v_t = (v_\omega + v_s) \qquad \text{....................(5)}$$

3.2. Point aggressiveness number

Point aggressiveness number is calculated on a point at point B as shown in Fig. 6 where length of contact is *l*. The resultant velocity vector as shown in Fig. 7. Is defined as: This expression is representing Point aggressiveness number for a particular point B at a distance l from the initial contact point.

$$v' = v_s.sin\,\theta \qquad \text{....................(6)}$$

$$\theta = \frac{l}{r_s} \qquad \text{....................(7)}$$

Since θ is small it can be approximated as:

$$sin\,\theta \approx \theta = \frac{v'}{v_S} \qquad \text{....................(8)}$$

$$\frac{v'}{v_s} = \frac{l}{r_s} \qquad \text{.....................(9)}$$

$$=(v_w + v_s)\hat{l} + \frac{v_s l_c}{r_s}\hat{j} \qquad \text{..................(10)}$$

$$v_n = \vec{v} \cdot \hat{n} \qquad \text{..................(11)}$$

$$= \vec{v} \cdot \left(-\frac{lc}{r_s}\hat{\imath} + \hat{\jmath}\right) \qquad \text{..................(12)}$$

$$v_n = \frac{v_s l_c}{r_s} - \frac{v_S lc}{r_s} + \frac{v_W l_c}{r_s} \qquad \text{..................(13)}$$

$$v_n = \frac{v_\omega lc}{r_s} \qquad \text{..................(14)}$$

As earlier defined the expression for point aggressiveness number is the ratio of v_n and v_t.

$$Aggr^* = \frac{v_n}{v_t} = \frac{\frac{l}{r_s} \times v_W}{|v_\omega + v_s|} \qquad \text{..................(15)}$$

$$\boldsymbol{Aggr^* = \frac{l}{|1+q|} \cdot \frac{1}{r_s}} \qquad \text{..................(16)}$$

3.3. Line aggressiveness number

As earlier defined the expression for line aggressiveness number is:

$$Aggr' = \frac{1}{l_C} \int_{l_C} Agg\gamma^* \, \mathrm{d}l_C \qquad \text{..................(17)}$$

Assumption: - length of contact is horizontal as θ is very small. Calculating line aggressiveness number for the whole contact length :- $(0 \to l_c)$

$$Aggr' = \frac{1}{l_c} \int_0^{l_c} \frac{y}{|1+q|} \cdot \frac{1}{r_s} . dy \qquad \text{.................(18)}$$

$$\boldsymbol{Aggr' = \frac{1}{|1+q|} \cdot \frac{l_c}{2r_s}} \qquad \text{.................(19)}$$

3.4. Undeformed chip thickness

An assumption is taken that the cross section of the chip formed while grinding is triangular (Malkin & Guo, 2008)

$$\text{Aspect Ratio (r)} = \frac{a_w}{h_m} \qquad \text{.................(20)}$$

No. of chips produce per unit time =N_c
(C= No. of Acive grains per unit area)

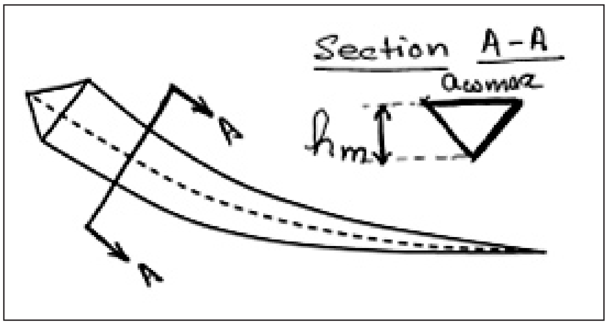


Fig. 8. Chip cross-section (Malkin & Guo, 2008).

$$\boldsymbol{h_m = \sqrt{\left(\frac{6}{cr} \times \frac{v_\omega}{v_s} \times \left(\frac{a}{2r_s}\right)^{1/2}\right)}} \qquad \text{.................(21)}$$

Since, $v_s \gg v_\omega$, The Equation for line aggressiveness number will be reduce to:-

$$Aggr' = \frac{v_\omega}{v_s} \cdot \frac{l_c}{2r_s} \qquad \text{.................(22)}$$

$$h_m = \sqrt{\left(\frac{6}{cr} \times \frac{v_\omega}{v_s} \times \frac{(2r_s a)^{1/2}}{2r_s}\right)} \qquad \text{.................(23)}$$

$$\boldsymbol{h_m = \sqrt{\left(\frac{6}{cr} \times Aggr'\right)}} \qquad \text{.................(24)}$$

3.5. Specific energy

Shear stress ($\vec{\tau}$) acting at the surface (s_c) defined as:-

$$\vec{\tau} = \frac{\overrightarrow{v_t}}{v_t}\tau = \frac{d\overrightarrow{F_t}}{ds_c} = \frac{d\overrightarrow{F_t}'}{dl_c} \qquad \text{.................(25)}$$

Specific energy (*e*) can be defined as:-

$$e = \frac{dP}{dQ} \qquad \text{.................(26)}$$

$$dP = \text{Power differential} = \overrightarrow{v_t} . d\overrightarrow{F_t}$$

$$dQ = \text{Material removal rate} = v_n ds_c$$

$$e = \frac{\overrightarrow{v_t} . d\overrightarrow{F_t}}{v_n ds_c} = \frac{v_t}{v_n}\tau \qquad \text{.................(27)}$$

$$\tau = e \, Aggr^* \qquad \text{.................(28)}$$

$$\overrightarrow{F_t}' = \int_0^{lc} \frac{\overrightarrow{v_t}}{v_t} \cdot \mathrm{e} \cdot Aggr^* \, \mathrm{d}l_C \qquad \text{................(29)}$$

$$\overrightarrow{F_t}' = \frac{\overrightarrow{v_t}}{v_t} \cdot \frac{\mathrm{e} \cdot a_x}{|1+q|} \qquad \text{................(30)}$$

$$e \propto \frac{1}{Aggr'} \qquad \text{................(31)}$$

3.6. Surface roughness

R_a= Surface Roughness obtained from Malkin and Guo (2008).

Surface roughness (R_a) Shinozaki et al. (nd) is dependent on input parameters as:

$$R_a = \frac{1}{9\sqrt{3}}.\left(\frac{v_\omega}{v_s}\cdot\frac{L}{(2r_s)^{1/2}}\right)^2 \qquad \text{................(32)}$$

where, L= Gap between alternate grain along the periphery = $\frac{2}{crh_m}$

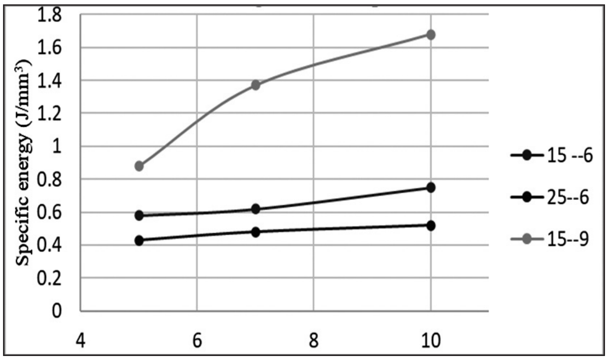
$$R_a = \frac{1}{9\sqrt{3}}.\frac{2}{3.c.r}.\frac{Aggr'}{a} \qquad \text{................(33)}$$

$$\boldsymbol{R_a = \frac{2}{27\sqrt{3}}.\frac{Aggr'}{a}} \qquad \text{................(34)}$$

4. Results and Discussion

The graphs were first plotted between the specific energy and depth of cut as well as surface roughness and depth of cut for nine different process parameters shown in Fig. 9 and Fig. 10. Here the plots are giving the values of specific energy and surface roughness for each set of parameters. This is a very tedious process.

So, to come up with better or alternative parameters to get the same surface finish or specific energy one can use aggressiveness number plot with respect to specific energy and surface roughness. These plots required no interpolation as shown in Fig. 11. Here, lets say for process parameters 15-9-5 with wheel diameter 187mm, the resulting surface fiunish is 0.88 um specicific energy = 0.27 J/mm^3 and aggresssiveness number (Aggr') + 5.17x10^{-5}. The same aggressiveness number can also be obtained from process parameters 18-9-7. This suggest that the operator has now got an opportunity to choose or optimize the process parameters which is best suitable for him to either increase productivity or to improve quality of the surface finished products.Hence, one has to calculate first aggressiveness number



Depth of cut in micron

Fig. 9. Specific energy vs depth of cut
From the graph 15_6 depicts 15 m/s wheel speed and 6 m/min table speed.

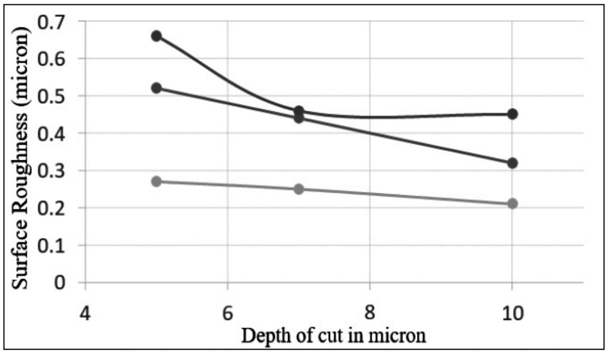


Fig. 10. Surface roughness vs depth of cut.

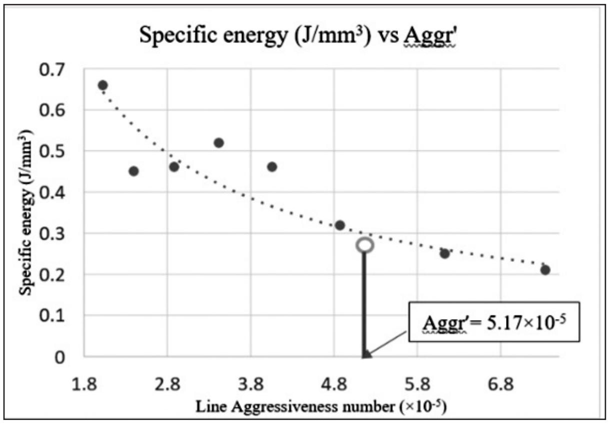


Fig. 11. Surface roughness (micron) vs Aggr'.

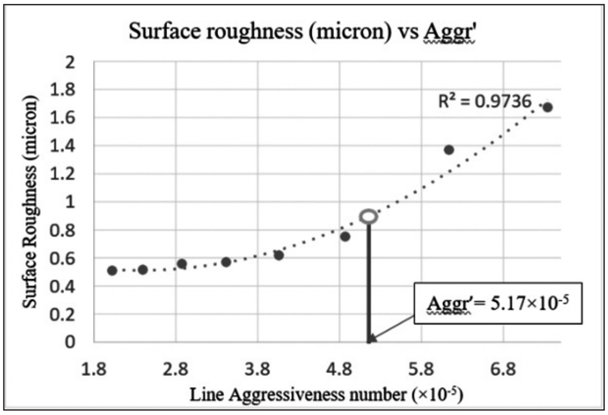


Fig. 12. Surface roughness and specific energy values are plotted with respect to aggressiveness number for three set of parameters vs- vw (15-6, 25-6 and 15-9) of which only depth of cut a is varied (5-10 micron).

and then based on that corresponding output surface roughness and specific energy can be estimated. One can also overcome the limitation of the maximum speed of the wheel or depth of cut selection as by changing other parameters and keeping aggressiveness number constant.

5. Conclusion

It is observed that with an increase in line aggressiveness number, the surface roughness value increases. The plot showing the variation of surface roughness with respect to the line aggressiveness number has an R^2 value of 0.9736. It is noted that the specific energy of the process is inversely proportional to the line aggressiveness number. As per industry demands, specific energy should be low to make the process efficient and hence lesser amount of energy is consumed per mm^3 of material removal. In a similar manner,the surfacer roughness value mustbe within a specific range to fulfil the required tolerances. Therefore, knowing the relation between aggressiveness number with surface roughness and specific energy can help in setting up of a constraint on manufacturer to get the desired output. Not only that,but the manufacturer can also have a database of selecting the correct input parameters instantly.

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