A new method for quantitative evaluation of diamond wheel sharpness in EDDG of advanced cutting tool material

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Abstract: In this paper authors propose a probability statistic based method for evaluating metal bonded diamond grinding wheel sharpness quantitatively. Grinding performances are decided by wheel sharpness and the conditions under which it is sharpened. It is also characterized grinding forces, cutting zone temperatures, power consumption and surface finish of components. Many times, in shop floors, the diamond wheels are used in a very inefficient manner due to lack of proper information about the wheel sharpness.

The correlation of wheel topography and its performance is studied through the employment of three dimensional surface characterization parameters. Wheel sharpness is analyzed by using the probability statistics in order to ascertain quantitative measurements of the sharpness of the wheel face. Wheel sharpness are evaluated by considering the influences of impulse energy, cutting speed, cross feed (depth of cut), and grit size on the same. Electrical discharge diamond grinding (EDDG) plays an important role in realizing highly efficient and accurate grinding of extremely hard electrically conductive tools materials. Electrical discharge diamond grinding, i.e., grinding with metal bonded diamond wheel under the , has been successfully applied in many instances since the early 19 Century for making cutting tools. EDDG is the most suitable process for manufacturing good quality cutting tools made of very hard electrically conductive tool material.
Ductile mode grinding of brittle materials has been of great interest due to its increasing industrial applications and academic demands for fundamental understanding of the ductile mode grinding mechanism.

Keywords: Electrical discharge diamond grinding, Metal bonded diamond grinding wheel

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INTRODUCTION

Recently, developments in the cutting tool industry have caused rapid increase in the use of advanced tool materials to distinctive progress. However, this has meant that grinding of these materials to form the cutting tools itself has also, progressively, become more difficult [1, 2]. As a solution to this difficulty application of hybrid machining processes has been the main trend observed in the cutting tool industry in need of advanced tool materials. The concept of electrical discharge diamond grinding (EDDG) which originated in the former USSR, is one of such processes used extensively in the manufacture and maintenance of the cutting tools made of in particular when they are tipped with electrically conductive very hard materials. A metal bonded diamond grinding wheel (MBDGW) is used in this process. MBDGW is used to remove material by mechanical action, and also acts as an electrode for electro discharge action, causing thermal softening of the material and hence machining by diamond grains become easier. EDDG allows the use of water or water based cutting fluid as a dielectric. Wheel speed and electrodischarge pulse parameters are adjusted to control the mechanical grinding and electrodischarge erosion during EDDG. As a result, the grinding wheel is constantly maintained in optimum state of sharpness or adjusted to the processing operation currently in hand. In EDDG, by adjusting wheel speed and electrodischarge pulse parameters, sharpness of the topography of the wheel can be adjusted to the machining task in hand.

However, a technical basis to utilize the diamond wheel to its best potential and in an economical manner require evaluation of diamond wheel's sharpness at the microscopic level ,i.e., from the considerations of grain work interaction which, in turn, will allow predicting wheel performance more accurately [7]. However, a methodology is required to allow the wheel sharpness to be used at its best potential. Clearly, the more realistic the wheel sharpness evaluation method, the more accurately EDDG performance may be predicted.

A number of methods for evaluating grinding wheel sharpness have been developed so far [3]

However, most of the suggested methods are laboratory based requiring standard equipment and cutting conditions. As a result, generalization or estimations of the grinding wheel sharpness are difficult to make with any degree of accuracy and to apply them to industry due to the limitation of equipment technology, staff and methodology. Hence, the term wheel sharpness is so far understood more in qualitative then in quantitative terms. This is more apt in industry where wheel sharpness has been specified by the operators based on their observations and experience. This empirical approach typically results in a highly variable situation as well as the tendency for too much dressing of the wheel in order to be on the "safe" side. This causes material waste and unnecessarily reduces the wheel's life. Therefore, it is necessary to develop a methodology in order to ascertain quantitative measurement of wheel sharpness.

Actual wheel sharpness can be considered the summation of the sharpness of individual grains/cutting edges [6]. Since the size of cutting edges is inherently random in nature, the wheel sharpness cannot be evaluated in a deterministic manner and one has to resort to a probabilistic approach. Therefore, the aim of the present work was to estimate MBDGW sharpness quantitatively using probability statistic. In addition, this work also evaluates influence of impulse energy, cutting speed, cross feed (depth of cut) and grit sizes on the wheel sharpness. Machining of advanced tool materials to form the cutting tools generally necessitates grinding with diamond wheels. Three flaring cup type wheels with diamond grit in 160/125,180/190 and 50/40 Russian mesh size respectively were used. Diamond concentration was 100 in all cases. The workpiece material chosen was Tolam-10 (Russian made) type cutting tool material. The result of this work can contribute to the analysis of EDDG performance, optimization of diamond wheel structures and optimization of diamond spark grinding process.

In the grinding of advanced materials such as optical glass, WC, ceramics and silicon has substantially grown with the widespread use of precision components made of such materials in various applications [4, 5].

Considering efficiency and precision, the abrasive grain protrusion height is a crucial parameter of grinding wheel's surface topography to get a high amount of total cutting. While, it is difficult get the protrusion height of an entire surface since there are three elements coexisting with their own geometrical shapes - depth, radius distance and azimuthal angle of flare type grinding wheel.

Concept of the method for evaluating wheel sharpness

In this version of wheel sharpness evaluation method, variations in diamond grain's protrusion heights from the wheel surface in the longitudinal direction-the grinding direction is estimated. When it is noted that an individual grain could have many tiny cutting points, then the variations in the heights referred to the level difference of such cutting points of the grain which produces atleast partial cutting above the similar cutting point of the previous active grain [8]. In fig.1,it may be seen that in the section Y=Yj, Δ ij is the level difference of one cutting edge of i-grain, which depends, among other parameters, on the applied normal force. Also, it may be seen that among all the cutting edges, only those denoted by α, β, gamma are assumed to be involved in material removal. It may be seen that Δ ij is one of the fractions of chip thickness or one of the numerous coordinates of the cross sectional area of the chip generated by a cutting edge of i-grain in the given section. Thus, the sum of all the Δ ij, obtained in various sections i.e. when j=1....P, is the cross sectional area of the chip, Si, generated by all the cutting edges of i-grain. It seems, that a wheel with a well sharpened face would have the close values of Si for different grains, because it contributes to uniform load distribution on the cutting edges, uniform wear characteristics of these edges etc. Therefore, as a measurement of wheel sharpness, the degree of Si values scattering for different grains, can be used; the less the better. Based on this idea, a wheel sharpness index, originally used for theoretical analysis of the variation in diamond grit heights on the wheel surface, is applied to measure the diamond grinding wheel sharpness in DSG. The following major assumptions are made to generate diamond wheel cutting surface in order to measure the wheel sharpness.

Following this, using a contact stylus type system, the grit protrusion heights are measured and quantitatively described by an appropriate probability density function.

Description and Formulation of the Wheel Sharpness Index

In this version of wheel sharpness evaluation method, variation in heights/separation distance between the surfaces of protruding diamond grains in the longitudinal direction-the grinding direction, is estimated. When it's noted that a grain could have more than one cutting edge, then the variation in the heights refers to the level difference of such cutting edge of the grain which produces atleast partial cutting above the similar cutting edge of the previous active grain. In fig.1, it may be seen that in the section Y=Yj, Δ ij is the level difference of one cutting edge of i-grain, which depends, among other parameters, on the applied normal force. Also, it may be seen that among all the cutting edges, only those denoted by α, β, gamma are assumed to be involved in material removal. It may be seen that Δ ij is one of the fractions of chip thickness or one of the numerous coordinates of the cross sectional area of the chip generated by a cutting edge of i-grain in the given section. Thus, the sum of all the Δ ij, obtained in various sections i.e. when j=1....P, is the cross sectional area of the chip, Si, generated by all the cutting edges of i-grain. It seems, that a wheel with a well sharpened face would have the close values of Si for different grains, because it contributes to uniform load distribution on the cutting edges, uniform wear characteristics of these edges etc.

Hence, if we denote selected average values of Si for all grains on the chosen surface as S, and selected deviation of Si values as σ, then the wheel maybe characterized quantitatively as function Ws= f (S, σ).It is quite obvious that the above function should be increasing with respect to the first argument S and decreasing with respect to the second argument σ respectively then, ratio S/σ. Therefore, as a measurement of wheel sharpness, the degree of Si values scattering for different grains can be used; the lesser the better. Based on this idea, a wheel sharp index, originally used for theoretical analysis of the variation in diamond grit heights on the wheel surface, is applied to measure the diamond grinding wheel sharpness in DSG. The following major assumptions are made to generate diamond wheel cutting surface in order to measure the wheel sharpness:

1. The diamond grain is ordinary sharp tip cone with semi cone angle, θ, as shown in fig.2. This geometry is consistent with observation showing abrasive particles to have negative rake angles.The difference in heights Δ ij is the depth of grain indentation.

2. Protruding heights on the wheel surface follow a gamma distribution. This distribution is consistent with the observations showing that during grinding of difficult to grind material, due to severe thermomechanical cycle, microspalling of the grain, takes place. Therefore, the topography of the wheel surface keeps on changing during "run-in" of the wheel. In view of this, the gamma probability density function is found to be more appropriate in order to describe the protruding heights of the diamond grains on the wheel surface.

3. Since only a portion of whole grain participates in the fine grinding process, an individual grain and its microcutting edges are symmetrical in shape.

4. The removal of the material from the workpiece is based on a rigid perfectly plastic material behavior i.e. the cutting edges will remove all materials that they encounter on their path. Although the elastic deflection of the workpiece will reduce the actual cutting depth (Δ ij), the possible pile up of material and the deflections are neglected.

5. Diamond grains along the circumferential and axial direction of the grinding wheel are distributed uniformly. This is based on the fact that during the manufacturing of diamond wheels, diamond grains, metal bond and the proper proportion of the filler are mixed thoroughly and the mixture is fed in to revolving drums, where all constituents mix together to form a paste. This process provides desired consistency to the mixture coats the diamond grains with adequate bond and produces uniform spacing between them. The paste is then placed in moulds to get the shape of the wheel.

6. There is no interaction between the bond and the workpiece. This is based on the fact that the DSG is able to adjust and maintain a constant grit protrusion and a stable grinding performance.

Based on these assumptions the relationship between wheel sharpness ws the selected average value of all chip cross sectional areas generated by the grains on the wheel surface S and selected standard deviation of these areas σ, is approximated as

$$Ws = S / \sigma$$

Techniques for calculating S and σ values are described in the next section.

3. Experimental Validation

3.1 Materials and Experimental

The adaption of ECCD technology to the universal tool and cutter grinder, model 3B642 (Russian made) was essentially achieved by fixing brushes in the grinding spindle head. By these brushes the power was supplied to the rotating grinding wheel (anode).The current source was connected to the brushes and the workpiece (cathode) respectively was achieved by brushes, which were fixed in the grinding spindle head. For this purpose, grinder spindle was modified for the supply of current into the spindle from which it then flowed to the rotating grinding wheel. As a power source, specially fabricated small sized generator was used whose characteristics could be controlled to provide optimum electrical parameters for EDDG of Tomal-10.As a dielectric fluid, tap water with small amount of soda was used. The materials of the workpiece were type-1 and type-2 carbides. The composition and the properties of these carbides are given in Table 1 and 2 respectively. For the experimentation bronze brass alloy bonded diamond wheels (flaring cup type) with 100% diamond concentration and the grit size 100/80 (USSR mesh) were used. These wheels and the grinding conditions shown in table -3 were selected in accordance with the experimental study on finding optimum grinding condition for EDDG of type-1 and type-2 carbides [11].After grinding the workpieces, worn wheel faces were photographed with help of Scanning Electron Microscope (SEM), Model jeol-JSM-50.

The experimental work for the quantitative measurement wheel sharpness can be divided into 2 parts. In the first part, the grit protrusion on the wheel surface is measured using a suitable wheel topography measurement system. The statistical parameters derived from such measurements are given in the form table and also a cumulative distribution function which is then approximated by a standard distribution function. Then the parameters for wheel cutting surface generation are determined. Using these parameters, generation of diamond grains on certain area of the wheel cutting surface is performed. Finally, variation in heights of diamond grains, S and σ values and then wheel sharpness index are calculated. In the second part, effect of some DSG parameters on the wheel sharpness index is analyzed.

3.2 Measurement of Protrusive Height of Diamond Grits Above the Bond

The protrusive heights of the diamond grits on the surface of three metal bond flaring cup wheels containing diamond grit in 160/125,180/90 and 50/40 Russian mesh size respectively and 100% diamond concentration in all cases were measured using specially designed stylus-based measurement system, also called as stylus profilometer. The diamond stylus was traversed on the surface to be measured over a predetermined distance of 15mm, 15mm, and 30mm for and diamond grain on the profile chart, a hard metal stylus of suitable size was mounted near Tomal-10 made indexable inserts under the conditions shown in table.Composition and mechanical properties at ambient temperature of workpiece material is given in table.

Fig shows the typical cutting surface of the wheel measured using stylus profilometer. The cumulative distribution functions of diamond grains protruding heights derived from such measurements on wheel surfaces is shown in fig.Its seen clearly from fig and that the diamond grain protruding heights of these three wheels can be approximated by a bounded gamma distribution function. Similar observations have been made by Katsev.The statistical parameters derived from this experiment are listed in the table

3.3 Parameters for wheel cutting generation

From the point of view of wheel cutting surface generation, the following parameters were used:

3.3.1 Mathematical equation for the diamond grain shape

The basic conical shape of the diamond grain can mathematically be formulated as follows:

$$Z = ZO - \theta\ [(X - XO)2 + (Y - YO)2]1/2 \quad \text{----------------------------------(1)}$$

where Z of the height of the grain, θ is the tangent of semi-cone angle of the cone shaped grit which is calculated by (Refer fig...)

$$\theta = \tan\text{-}1\ (R/h)$$

where, R is the radius of the cone shaped grain and h is the grain height. X, Y, Z are the coordinates of cone summit.

3.3.2 Diamond grains protruding height distribution on the wheel surface

The height from the bond surface to the very top of the diamond grit, delta, is not the same for all the diamond grains on the wheel surface but are statistically distributed between a smallest value, and a larger value. Generally, this distribution can be well described by an appropriate bounded probability function. In this work, gamma probability function is used. This function is expressed mathematically as

$$f\ (\text{deltai}) = (\beta\ \alpha + 1).e\text{-}\beta.\text{deltai}\ .\text{deltai}\ \alpha\ /\ (\alpha+1)!$$

On the basis of calculated values of mathematical expectation and variance, α and β parameters for different grain sizes were calculated as

$$\alpha = 6.058 - 0.083\ Z + 0.00076\ Z2$$

$$\beta = 0.555 - 0.0056\ Z + 0.00003\ Z2$$

where Z is the grain size which is the mean diameter of the grain.

3.3.3 Diamond grains mean diameter

The mean diameter dmean, of the grain was determined as

$$dmean = (dmax + dmin)\ /\ 2$$

where dmax is diameter of sieve through which the grain passes and dmin is that on which grain remains. Table 6 gives values of mean grain diameters for different grain sizes.

3.3.4 Diamond grains distribution along X and Y directions

It has been assumed that the spacing's between two consecutive grains along X and Y directions follow uniform distributions. These distributions are shown in Fig...

3.3.5 Number of diamond grains on the wheel surface

The number of abrasive grains on the grinding wheel surface was determined by counting the cutting points on the profile trace obtained from the profilometer. The number of grains on certain cutting surface area of the wheels with different grain sizes is given in table 6.

Function corresponding to the probability density function f (delta).Thus the location of the grains on the wheels surface is decided. Figure shows the simulated wheel cutting surface.

3.4 Determination of variation in heights of diamond grains

Once the aforementioned parameters are known, random number generator is used to simulate the positions of diamond grits referring to the principles of the Monte Carlo method. After the diamond grains on an unit cell of certain size of the wheel surface are generated, as schematically as shown in fig The coordinate system XYZ is fixed to that unit cell at point O. Let the unit cell be divided into n equally spaced divisions along the Y direction. The line m at the distance Ymax/2 denotes one of such divisions that intersect the cutting points of N number of diamond grains. Then, the protrusive height, Δ of all these cutting points are determined using the formula

deltai = Zi - a [(m - Yi)]1/2

As a result, a set of delta1,2,3,4..................n values are obtained. On the basis of these values, variation in heights of the cutting points for each grain in the given division, Δ ij are determined. Similarly, Δ ij for other divisions are calculated. As a result, a set of Δ ij values for various cutting edges of an individual grain are obtained. By integrating the values, the cross sectional area of the chip, Si, generated by all the cutting edges of an individual grain is obtained. In the present work trapezium method is used for integrating the Δij values. Similarly, Si for other grains are calculated which when integrated, the cross sectional area generated by all the grains, S is obtained.

3.5 Calculation of S and σ values

When the sum of cross sectional areas generated by all the grains on the simulated wheel surface , S, is known the mean cross sectional area can be determined as

S' = S/n = (S1 + S2 + S3 +........+ Sn)/n

and the standard deviation of the cross sectional areas from the mean value , σ, is determined as

σ= [{(S1 - S')2 + (S2 - S')2 +.......+ (Sn - S')2} / n]1/2

where n is the number of diamond grains on the simulated area of the wheel surface. The calculation and also the assessment is carried out by computer and the results obtained can be displayed as graphs and can also be output as text file. The flow chart for calculating the wheel sharpness is shown in fig .Table below gives values of S, σ and Ws in tabular form for convenience.

3.6 Effect of DSG process parameters on wheel sharpness index

To assess the effect of DSG process parameters on wheel sharpness index, grinding tests were carried out on Tomal - 10.The workpiece was ground with wheel that had been sharpened by DSG process. The test conditions are entered in the corresponding diagrams.

3.6.1 Effect of single discharge energy on the wheel sharpness index

As maybe seen in fig 2, with the decrease in single spark energy, wheel sharpness index initialy increases and after that decreases. The maximum Ws is when the pulse frequency, f = 44 KHz. At f = 22KHz, intensified sharpening takes place. However, greater spread in the values of variation in heights of the cutting points, have an influence on σ.Decrease in Ws at f = 66KHz can be explained by the fact that at small discharge energy (6 X 10-4 Joule), active self sharpening of the wheel surface does not take place. Consequently, difference in the height of protrusion of all the tips of the grains becomes much reduced. As a result, the mean cross sectional area generated by the grains is less.Therefore the sharpness index has lower value.
The above results show that when grinding Tomal-10, the pulse frequency, f= 88KHz be employed in order to maintain the wheel sharpness at high level.

3.6.2 Effect of the wheel speed on sharpness index

The effect of the wheel speed on the sharpness index during the DSG of Tomal-10 is shown in fig 3.The wheel sharpness index diminishes as wheel speed increases. There are various reasons for the shape of this curve. The higher speeds lead to reduced cutting cross sections with the result that the load on the grains, but also the removal per grain are reduced. Neither the increasing wheel speed nor the higher engagement frequency of the diamond grains on the diamond layer can compensate for the diminishing removal and the wheel sharpness index as well. In addition, the sliding effect is intensified by the higher speeds. These mechanisms lead to reduction of removal at higher speed.

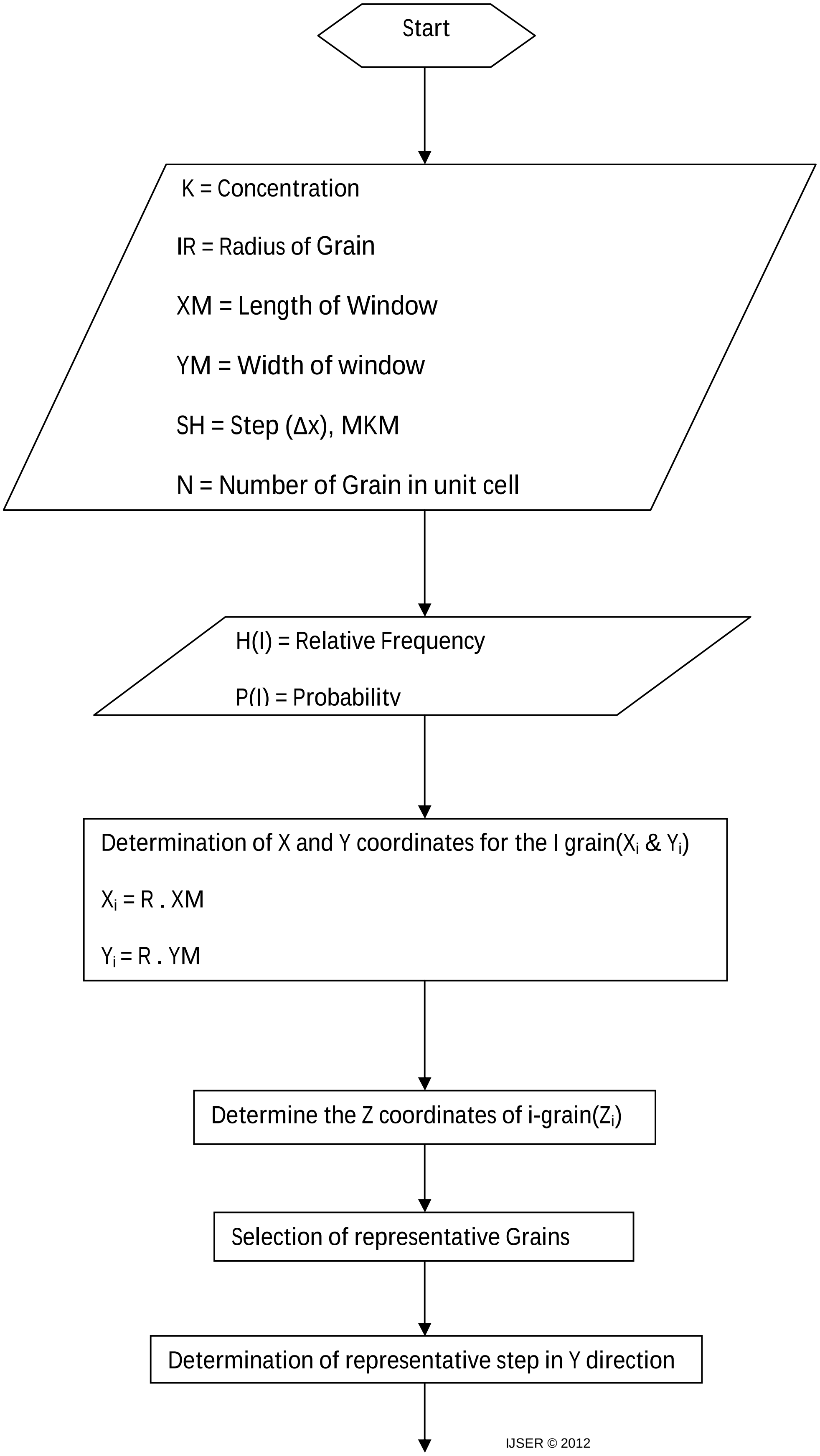
3.6.3 Effect of the cross feed on the sharpness index

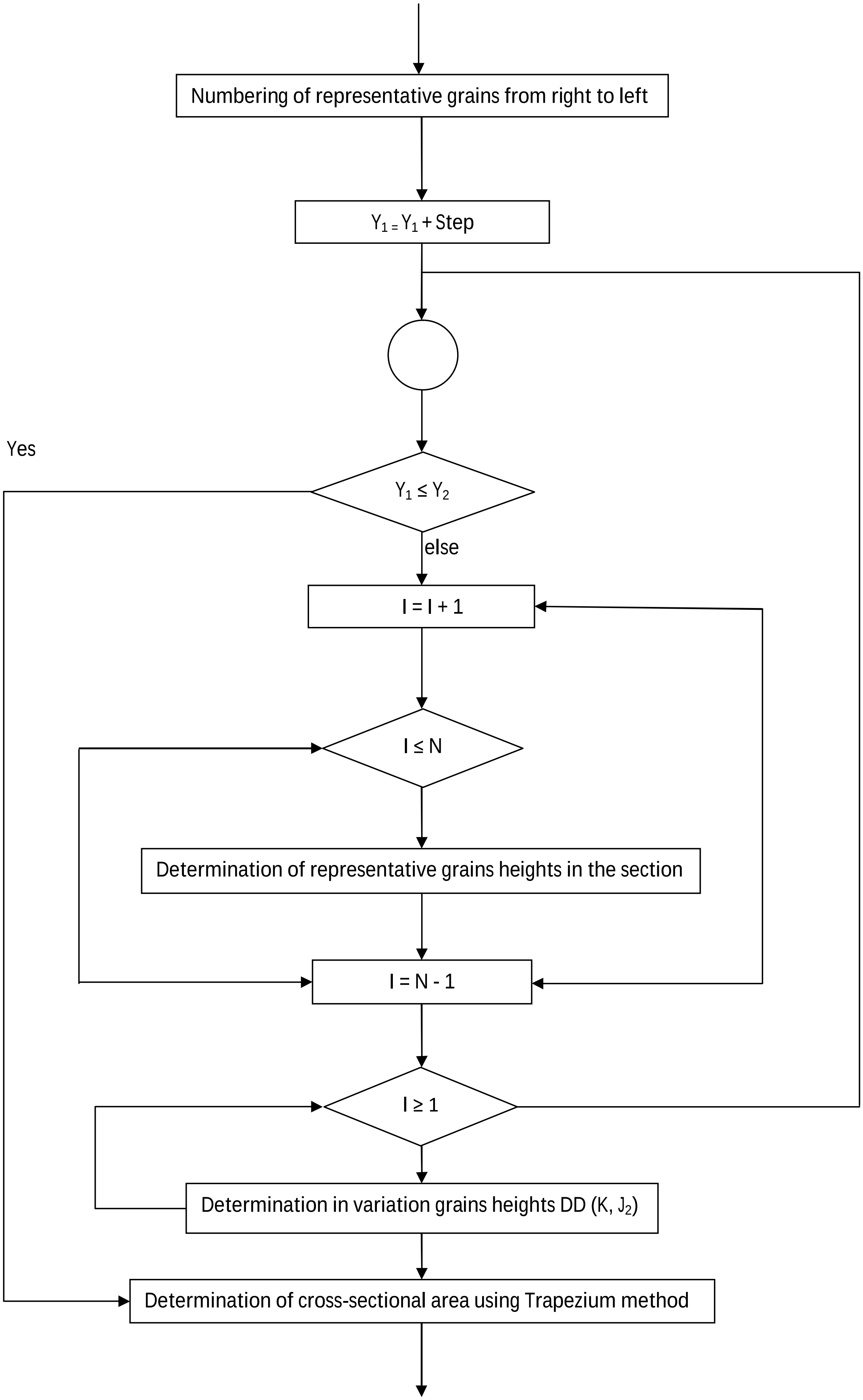
The sharpness index of the diamond wheel with grit size 100/80 is plotted by function of the cross feed in fig 4 below.The WS increases with increase in cross feed. This can be explained by the fact that, when the workpiece is hard, at a small cross feed only some of the diamond grains penetrate the material, most of them only slide and thus remove less material. The grain tips are correspondingly blunted on the workpiece and thus causes glazing of the wheel. Consequently, cross sectional area generated by the grains becomes small and therefore the wheel sharpness index decreases at small cross feed. Penetrate with increase in cross feed, the diamond grains penetrate farther into the material and thus remove more for each grain engagement. As a result, cross sectional area generated by the grains increases and therefore the wheel sharpness index also increases.

3.6.4 Effect of the grit size on sharpness index

Diamond wheels with fine grit size are normally used for finishing Tomal-10.A comparison of the wheel sharpness indices with 50/40,180/90 and 160/125 Russian mesh wheels reveals no significant difference in the wheel sharpness indices for 180/90 and 160/125 wheels, whereas the sharpness index is lowest for the finer grained (50/40) wheel (fig 5).Despite the increase in the number of active grains with decreasing grit size, the removal rate does not, however, achieve the values achieved with the coarser grained wheel which is attributed to the larger sliding area that counteracts the increase in material removal rate, i.e., with a fine wheel size, the workpiece rests on several tips and slides. With coarser grain sizes, the grains penetrate further into the material and thus cause the slightly higher tangential forces, with the result that the material removal also increases.

The comparative tests with the above wheels show that Tomal-10 should be ground with coarser grained diamond wheels.


Start
K = Concentration
IR = Radius of Grain
XM = Length of Window
YM = Width of window
SH = Step (Δx), MKM
N = Number of Grain in unit cell
H(I) = Relative Frequency
P(I) = Probability
Determination of X and Y coordinates for the I grain(X_i & Y_i)
X_i = R . XM
Y_i = R . YM
Determine the Z coordinates of i-grain(Z_i)
Selection of representative Grains
Determination of representative step in Y direction


Numbering of representative grains from right to left
Y1 = Y1 + Step
Yes
Y1 ≤ Y2
else
I = I + 1
I ≤ N
Determination of representative grains heights in the section
I = N - 1
I ≥ 1
Determination in variation grains heights DD (K, J2)
Determination of cross-sectional area using Trapezium method

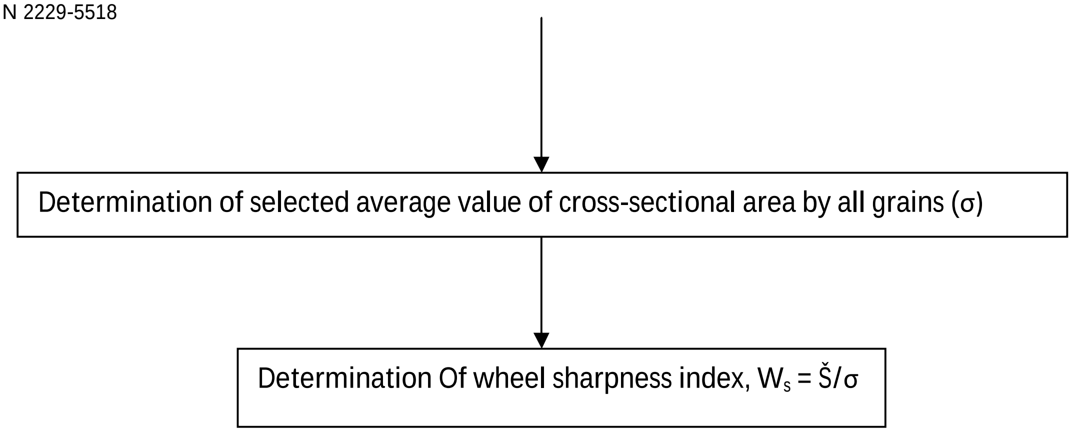
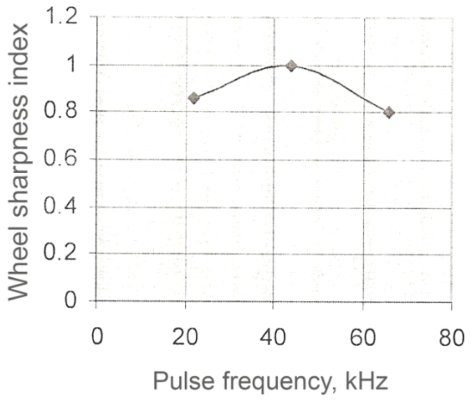
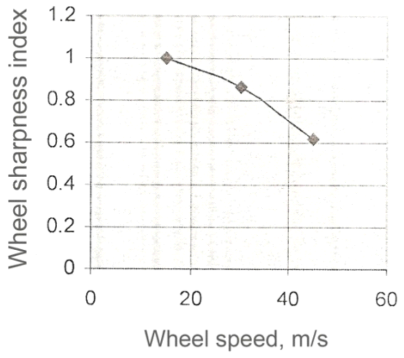


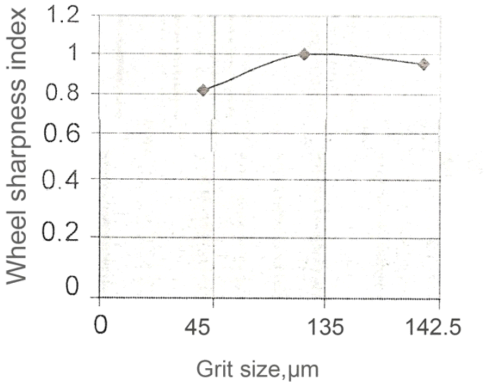
Fig.1 Flow chart for calculating the Grinding Wheel Sharpness





(starting from left) Fig 2 : Relationship between the pulse frequency and wheel sharpness index

Fig 3: Relationship between the wheel speed and wheel sharpness index



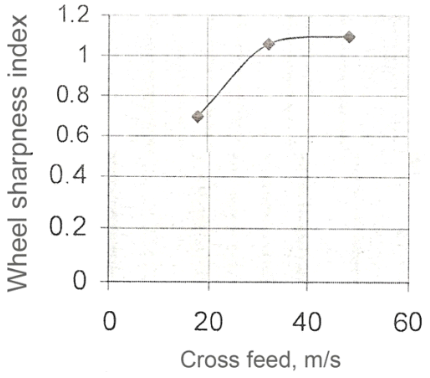
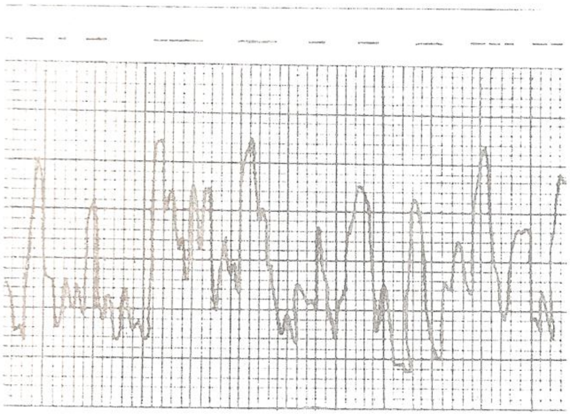
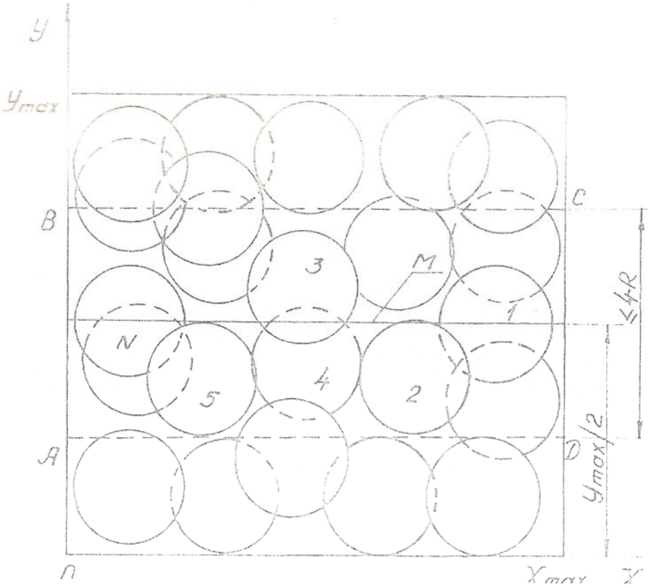


Fig4: Relationship between the grit size and wheel sharpness index

Fig 5: Relationship between the cross feed and wheel sharpness index




y
ymax
B
C
3
M
1
N
5
4
2
≤4R
A
D
ymax/2
0
Xmax
X

Wheel grit size (Russian mesh)	**50/40**				**100/80**				**160/125**			
Modeling Variant	I	II	III	Mean	I	II	III	Mean	I	II	III	Mean
Area of the unit cell in consideration (mm^2)	**0.86**	**0.83**	**0.83**	**0.84**	**1.76**	**1.79**	**1.79**	**1.78**	**5.49**	**5.55**	**5.49**	**5.51**
Number of grains selected on the unit cell	**22**	**29**	**29**	**27**	**23**	**26**	**20**	**24**	**32**	**24**	**23**	**26**
Number of cross sectional areas generated by the grains on the unit cell	**11**	**8**	**8**	**9**	**14**	**13**	**10**	**12**	**8**	**11**	**9**	**9**
Integrated cross sectional area generated by individual cutting grains (mm^2 x 10^{-6})	**49.5**	**45.5**	**45.5**	**46.83**	**86.2**	**87.5**	**89.3**	**87.2**	**100.1**	**115.4**	**132.5**	**116**
Mean of the cross sectional areas generated by all grains (mm^2 x 10^{-6})	**4.5**	**6.18**	**6.18**	**5.62**	**7.1**	**7.4**	**6.8**	**7.1**	**14**	**16.2**	**17.5**	**15.9**
Standard deviation of cross sectional areas from the mean value (mm^2 x 10^{-6})	**3.85**	**8.89**	**8.89**	**7.21**	**6.72**	**6.56**	**6.62**	**6.63**	**8.89**	**9.31**	**10.09**	**9.7**
Wheel sharpness index, W$_s$ (e^{-15})	**0.59**	**0.69**	**0.69**	**0.65**	**0.82**	**0.84**	**0.87**	**0.83**	**1.57**	**1.62**	**1.69**	**1.62**

Conclusion:

The above discussion demonstrates that the following conclusions:

Theoretical measurement of particle and surface sharpness has been developed.

The protruding height of each grain is measured and wheel sharpness has been evaluated and demonstrated in a tabular form.

The effects of single discharge energy,grit size,cross feed,DSG process parameters,wheel speed were studied.

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