A STUDY ON ELECTROCHEMICAL GRINDING OF SMALL DIAMETER SPECIMENS MADE OF TUNGSTEN CARBIDE

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Introduction

Electrochemical grinding is a relatively new process that has already been firmly established in industry, and has an expanding scope of application. The material removal in the process of ECG is most commonly done by means of the face of a diamond-impregnated wheel, so the boundaries of the gap between the wheel and the workpiece can be considered to be parallel. This fact facilitates to carry out relatively simple model tests, as it was done by COLWELL [1], BECKER-BARBROCK [2] and HOPENFELD [3]. In spite of the possible simplification given by parallel working gap, the abrasive-assisted electrochemical process is not quite known in detail. No equation describing the complex electrochemical-mechanical material removal has been established now. PAHLITZSCH and MARTEN [4] have derived empirical equations for calculating the removal rate from the current density and pressure, but COLVELL [1] and PAHLITZSCH [5] have demonstrated their limited applicability.

Electrochemical grinding evidently has many advantages over conventional grinding of carbides, the most significant being high productivity and low wheel wear, entraining an important decrease in machining costs. That is why the use of ECG has been extended to other fields, like peripheral or surface grinding, internal grinding and cylindrical grinding.

GEDDAM and NOBLE [6] have shown that peripheral grinding is of great importance in production engineering and their experimental investigation has proved the capability of ECG in this field of machining. In this paper experimental results on the cylindrical grinding of small diameter specimens made of carbide are presented.

Investigation of electrochemical cylindrical grinding

A comparison between different kinds of electrochemical grinding processes attests that the greatest difference between them is due to the shape of the working gap. In both peripheral and cylindrical grinding the surfaces of electrodes are other than parallel as shown by SHAN [7] and KOLL [8].

Cylindrical electrochemical grinding is often to be considered as an inefficient application of the electrochemical process. Namely, primarily material removal is the function of the current drawn through the gap, and large current means intensive metal removal, but requires a large area of contact between the electrodes if arcing, catastrophic wheel wear and surface damage are to be avoided.

PEARLSTEIN [9] has experimentally shown that sparking potential largely depends upon the area of contact and applied pressure, and concluded that its value must exceed 0,25 to 0,3 cm^2 if the set pressure is 3 kp/cm^2. Similar results have been obtained by PAHLITZSCH and VISSER [10], namely, that electrochemical grinding is superior to mechanical grinding for areas of contact over 0,6 cm^2.

On the other hand, in case of high current densities, to give satisfactory supply of electrolyte, the grinding area should be smaller than 1,5 cm^2 in the direction of cutting [10]. The area of contact has therefore to be considered as one of the significant problems in ECG. Conventional cylindrical grinding obviously provides only a small contact area and that is why until recently it could not be used economically in the electrochemical process.

The problem of quasi-line contact can be eliminated by the deep-grinding technique and by a special purpose grinding machine presented by AMRHEIN [11] and KOLL [8].

By applying the deep-grinding technique, the area of contact can be sufficiently increased and set in the required range of 0,25 to 1,5 cm^2.

The WENDT firm has developed the DIATOS electrochemical cylindrical grinder of an application range of 80 to 550 mm in diameter, providing a stock removal far beyond expectations.

The diameter of the grinding wheel normally used is 400 mm. In production engineering, or rather in cutting tool making in many cases the diameter of the tool to be machined is much smaller than that of the workpiece mentioned before. There is a serious industrial need for machining parts or cutting tools made of solid carbide or of hardened steel materials, or in some occasions the dimensions of the grinding wheel arc are limited by accessibility aspects, for instance, in machining broaches.

Investigation of the influence of wheel and workpiece dimensions on material removal

Analysis of the area of contact

Our experimental work has been basically intended to produce small diameter push broaches of solid carbide. This problem has been approached by machining grooves by plunge-in grinding, which sufficiently simplifies investigation and gives information of great importance for more complicated cases. To obtain useful data, the first stage was to determine the size and shape of the area of contact. In cylindrical deep grinding the area of contact depends upon the diameters of the workpiece and wheel, the width of the wheel and the depth of cut. Cylindrical grinding can be approached from the side of

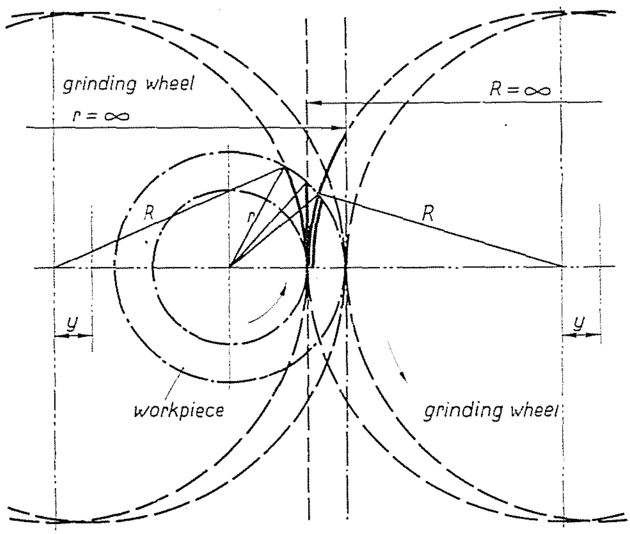

Fig. 1. A schematic diagram for calculating arc and area of contact obtained from possible methods of cylindrical grinding

surface grinding, i.e., surface grinding can be considered as grinding a cylindrical specimen of infinite radius, as shown in Fig. 1.

Fig. 1 is a schematic representation of both surface and cylindrical grinding, the workpiece of radius r being on the left-hand side and the wheel of radius R on the right-hand side. y means the depth of cut. In general, the grinding of a cylindrical workpiece can follow one of the four different methods as shown in Fig. 1:

(i) Both workpiece and wheel radii have finite values and the workpiece is ground by the outer periphery of the wheel. That is the conventional cylindrical grinding.

(ii) The workpiece radius r has an infinite value or in other words, the workpiece is flat, and the wheel radius has a finite value. This is the conventional surface grinding.

(iii) Both workpiece and wheel radii have finite values and the workpiece is inside the wheel. In this case a stringent requirement is that the wheel radius must be considerably greater than that of the workpiece because the wheel works by its inner periphery. For this case, the wheel location is seen on the left-hand side.

(iv) The workpiece radius has a finite value but the wheel radius is infinite. In this case the cylindrical grinding is done by the face of a cup wheel.

The geometrical axes of the wheel and workpiece include a right angle. Omitting mathematical derivation, the arc of contact can be calculated by the equations:

(i) $$a = \frac{D\pi}{360^\circ} \text{arc cos} \left[1 - \frac{2y}{D} \frac{D + y}{D + d - 2y}\right]$$

(ii) $$a = \frac{D\pi}{360^\circ} \text{arc cos} \left[1 - \frac{2y}{D}\right]$$

(iii) $$a = \frac{D\pi}{360^\circ} \text{arc cos} \left[1 - \frac{2y}{D} \frac{d - y}{D - d + 2y}\right]$$

(iv) $$a = y \sqrt{\frac{d}{y} - 1}$$

where D — diameter of the wheel
d — diameter of the workpiece
y — depth of cut

In general, the arc of contact is a function of both workpiece and wheel diameter and the depth of cut, apart from special cases "ii" and "iv", where one of the diameters is virtually neglected.

It is evident that the area of contact is proportional to the arc where the constant of proportionality is the width of the grinding wheel.

From the viewpoint of cylindrical grinding the case "ii" can be omitted and the rest have to be analysed. For the sake of easy understanding of the functions obtained, each of them has been plotted by a HEWLETT-PACKARD plotter. The arc and area of contact as a function of depth of cut are shown in Fig. 2. Because of practical aspects, the diagrams have been plotted with the actual sizes of the experimental workpiece and wheel. The diameters of test specimens and wheel are 30 mm and 100 mm respectively. The width of the grinding wheel is 10 mm.

For a given depth of cut it is quite clear that version "iii" gives the largest area of contact and version "i" promises the smallest one, or inversely, a predetermined area of contact can be achieved at the smallest depth of cut by means of version "iii". Obviously, for grinding small-diameter specimens, the method "iii" should advisably be used. Although this version of ECG

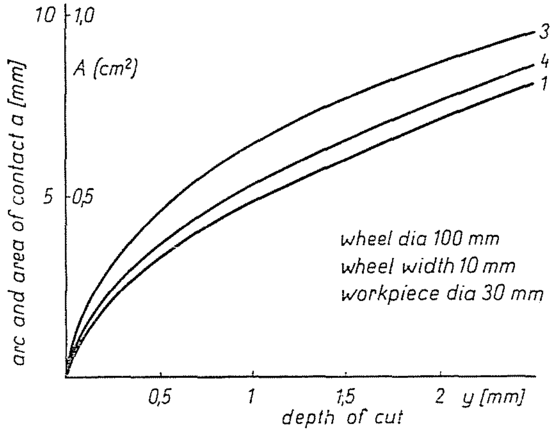

Fig. 2. Arc and area of contact obtained by different methods of cylindrical grinding vs depth of cut

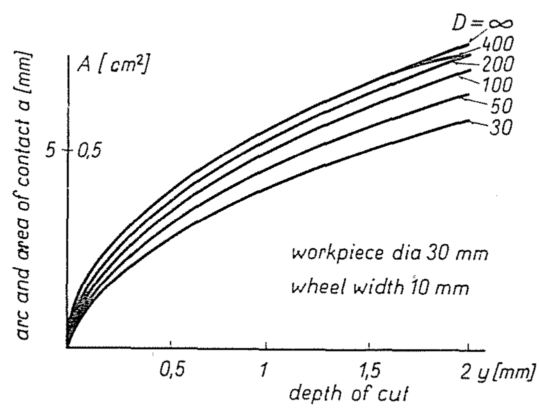

Fig. 3. Arc and area of contact at different constant values of wheel diameter vs depth of cut

implies certain difficulties in design of such a machine, it would be useful to investigate this method.

In Fig. 3 the arc and area of contact are plotted against depth of cut for different constant values of wheel diameter, in case of version "i". Setting a constant depth of cut it can be concluded that the area of contact increases with increasing wheel diameter, but there is no considerable difference between values belonging to identical wheel diameters. It is quite surprising that infinite wheel-diameter version "iv" produces nearly the same result as the diameter of 400 mm. Therefore, and because of wheel cost, it is not reasonable to apply great diameter wheels in such conditions. Notice that for grinding large diameter workpieces, the wheel diameter should appareantly be increased.

In Fig. 4 the arc and area of contact are plotted versus depth of cut and the workpiece diameter means the parameter. The curves in Fig. 4 belong to increasing workpiece diameters from 10 mm to infinite diameter, equivalent to the case of surface grinding.

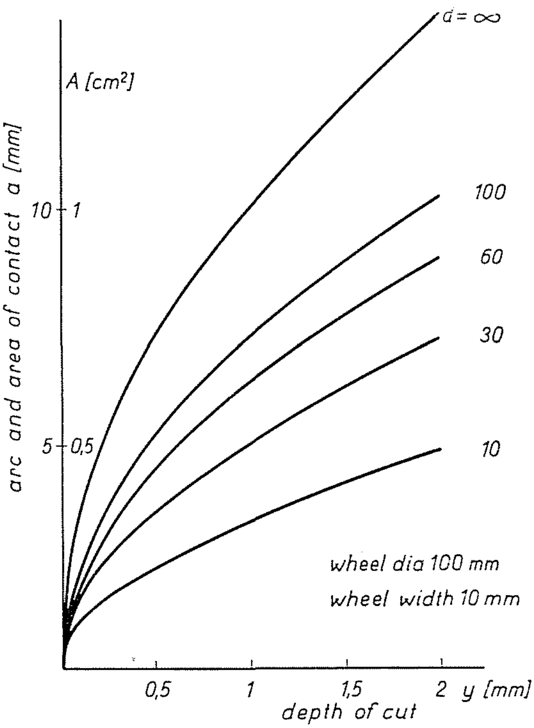

Fig. 4. Arc and area of contact at different constant values of workpiece diameter vs depth of cut

Analysing the area of contact at a constant depth of cut leads to the conclusion that in the given conditions, i.e. wheel dia. of 100 mm and width of 10 mm, the area of contact increases with increasing workpiece diameter. It is remarkable that the areas of contact obtained with workpiece diameters of 30 mm and 100 mm differ by nearly as much as those for dia. 100 and infinity. On the other hand, a workpiece dia. of 30 mm is seen to be adequately ground electrochemically in the range of 1,0 to 0,5 mm depth of cut because it still produces the required area of contact greater than 0,25 cm^2.

Material removal

Material-removal rate is another question of great importance in ECG. When cylindrical specimens are to be ground by the deep-grinding technique, the volume of material removal depends upon the diameter of the workpiece,

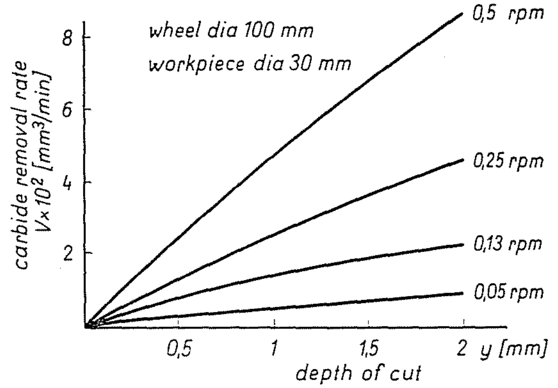

Fig. 5. Carbide-removal rate at different constant values of number of revolution vs depth of cut

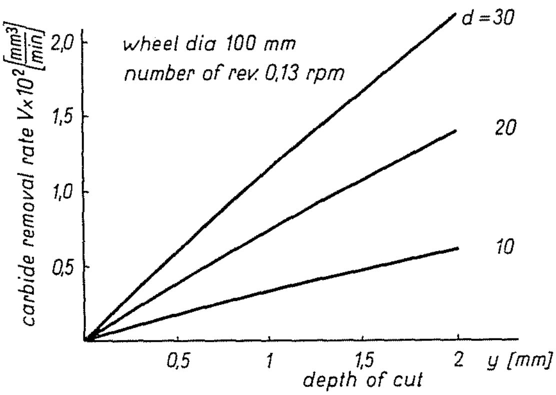

Fig. 6. Carbide-removal rate at different constant values of workpiece diameter vs. depth of cut

the width of wheel and the depth of cut. The removal per unit time, i.e. the rate of removal, is determinded by the number of revolutions. The derivation of removal rate from the geometry of cylindrical grinding yields the formula

$$V = b \cdot \pi \cdot n \cdot y\,(d - y)$$

Analysing this function, removal rate is seen to be a linear function of the width of wheel, number of revolutions and of the diameter of the specimen ground, and a quadratic function of depth of cut.

The equation of removal rate was plotted against the depth of cut by a HEWLETT—PACKARD plotter, as shown in Figs. 5. and 6. In Fig. 5 the parameter is the number of revolutions, and in Fig 6. the diameter of the workpiece. Analysing curves in Fig. 5, it turns out that in the region of low speed of rotation the curve can be well approximated by a straight line but for higher speeds, the straight line gives a slightly poorer approximation without causing a great error compared with the exact function. The opposite behaviour is seen in Fig. 6. The diagrams belonging to greater diameters can be approximated by a straight line, with no serious error in the range of small diameters.

The behaviour of this function can be explained by the fact that the equation of the removal rate is composed by a linear and a quadratic function of depth of cut. Since the second member is very small compared to the first one, it can practically be neglected.

Equipment

Machine tool

Experiments were carried out by means of a properly modified EU 630 type heavy engine lathe. The compound rest was removed and an electrically insulated tool post grinder was mounted on the carriage.

The diameter of the main spindle was 100 mm, and that of the grinder 80 mm. The lathe had a 14 kW, the grinder had a 1,5 kW drive. In order to set a very low rotation speed and feed rate, the drive in gear of the lathe was driven by an extra speed-reducing gear-box. The speed of rotation could be changed from a minimum value of 0,106 rpm up to 5 rpm. The electric current was supplied by a 400 A WENDT d.c. generator through brushes on both the main spindle and the grinder spindle. With the help of the generator the voltage was infinitely variable in the range of 5 to 10 V.

Grinding wheel

In our experiment a diamond-impregnated metal-bond grinding wheel, 100 mm in diameter and 10 mm in width, was applied. Diamond concentration was 3,3 carats/cm^3 and grit size 100/120 μm. The width of the layer containing the diamonds was 2 mm.

Specimens

The grinding specimens for this investigation were made of P 30 grade (ISO) carbide 30 mm size in diameter and 60 mm in length. The composition of carbide investigated was Co 10%, WC 82% and TiC 8%. Other features were: specific weight 13,1 p/cm^3, microhardness HV 1500 kp/mm^2, bending strength 170 kp/mm^2.

Electrolyte

The composition of the electrolyte used was an aqueous solution of WENDOLYTE salt at a concentration of 1,8 kg per 20 litres of water. The measured pH value was 9,5. Its temperature was kept between 25 °C to 30 °C. Electrolyte supply was 5 litres/min.

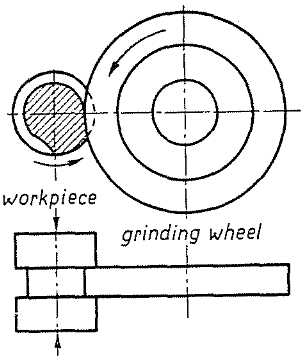

Fig. 7. A schematic representation of cylindrical deep-grinding technique

Test procedure

In the tests the method used was electrochemical deep-grinding technique version "i", shown in Fig. 7, and the carbide removal was investigated as a function of the depth of cut at a constant applied voltage of 7 V and rotation speed of 0,13 rpm.

The wheel peripheral speed was kept constant, 17 m/s. The theoretical carbide removal is proportional to the current drawn through the gap. In electrochemical cylindrical grinding, material removal is forced by the rotation speed of the workpiece. That is why electrochemical efficiency is largely determined by the speed of rotation. The ratio of mechanical to electrochemical removal is obtained from the current. In our experiments, in some cases the surface roughness has been recorded.

In Fig. 8 the area of contact, the total removal rate, the current measured, the current density and the resistance of the gap are plotted against the depth of cut. It is obvious that the best electrochemical efficiency belongs to the minimum distance between the curves of to tal removal rate and current. The minimum distance is in the range of 1,0 to 1,5 mm in depth of cut. In this range the area of contact varies from 0,5 to 0,7 cm². At the value of 0,5 mm in depth of cut, sparking occurs, the distance between the two curves is reduced due to the resulting higher current.

Under these circumstances sparking causes intensive wheel damage and very rough surface finish. The decrease of current, over 1,75 mm in depth of cut, can be explained by hydrogen evolution in the gap, increasing electrolyte resistance. Analysing the effect of current density, it can be concluded that the electrochemical action is most efficient in the range 1,0 to 1,75 mm in the depth of cut, slightly up to the right, as it has been obtained from the curve of current. This is because the area of contact increases with increasing depth of cut.

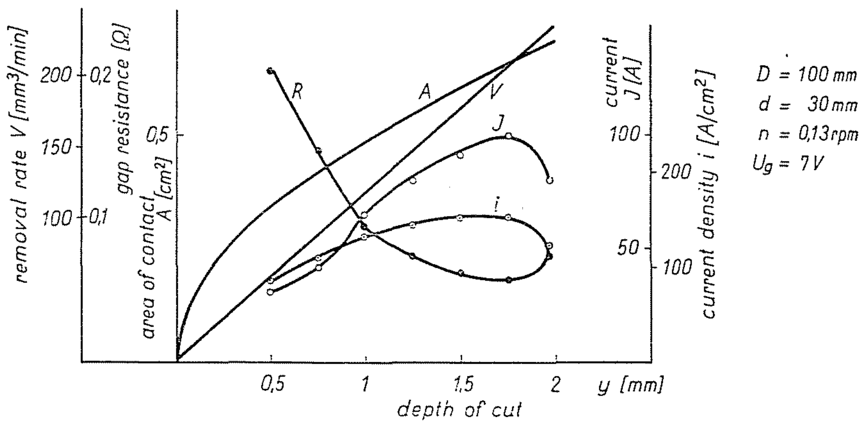

Fig. 8. Carbide-removal rate, gap resistance, current density, area of contact and total current versus depth of cut

Colwell [1] has proved that gap resistance shows a marked sensitivity to voltage, current and feeding force. It must be underlined that feeding force is produced by the speed of rotation in cylindrical electrochemical grinding. Gap resistance gives a good indication of significant deviation from optimum operating conditions. The curve of gap resistance calculated from voltage drop in the gap and current in Fig. 8 is shown to give a good correlation with the curve of current density.

This is particularly interesting, since both contact area and total removal are nonlinear functions of depth of cut. Each of the curves of current, current density and gap resistance has an optimum at the same value of depth of cut, but it is slightly up to the right from the optimum obtained from the comparison of total removal rate and total current.

This alteration is probably caused by nonlinear changes of process variables.

Conclusions

From the results of theoretical and experimental analyses of electrochemical cylindrical grinding of small diameter specimens made of tungsten carbide, the following conclusions can be drawn:

Analysis of possible versions of electrochemical cylindrical grinding of small diameter specimens made of tungsten carbide has shown that method "iii" promises the best electrochemical performance due to the largest area of contact, compared to other possible methods. In other words, for a constant area of contact, the version "iii" of cylindrical grinding gives the smallest depth of cut. This is a great advantage if depth of cut is predetermined because of certain reasons, for instance, if allowance is small. On the other hand, some difficulties arise in connection with design of grinding machine suitable for this kind of operation.

The deep-grinding technique is most frequently applied for grinding cylindrical specimens by ECG. Using this method "i", the analysis has shown it would not be reasonable to apply a very big diameter grinding wheel if a given diameter workpiece is to be ground, because there is no considerable increase in area of contact with increasing wheel diameter. The optimum size of wheel diameter depends upon the workpiece diameter.

The experiments have proved that the electrochemical external deep-grinding technique is advantageous for machining specimens made of tungsten carbide from the size of 15 to 20 mm in diameter.

In the deep-grinding technique total material removal is forced due to the forced coupling of the wheel and workpiece and presumably there exists an optimum of electrochemical removal in dependence on the rotational speed. A similar hypothesis can be proposed for the applied voltage, to be supported by further tests. Applying a wheel diameter of 100 mm and a width of 10 mm, a workpiece diameter of 30 mm and material made of P 30 grade carbide, a voltage of 7 V, a rotational speed of 0,13 rpm, the best electrochemical efficiency was obtained at a depth of cut of 1,0 to 1,5 mm. It meant a material removal rate of approximately 150 to 170 mm^3/min.

Surface roughness recorded in some cases by a Perth-O-Meter universal measuring instrument did not exceed the value of 0,7 μm in R_a and had a minimum value of 0,3 μm.

Summary

This paper describes research carried out on the cylindrical electrochemical grinding process. The possible versions of grinding cylindrical specimens have been theoretically analysed. The arc and area of contact as well as material removal, of great importance from the viewpoint of the electrochemical process, have been investigated. The advantages of electrochemical over conventional grinding can be utilized when small -diameter specimens of solid carbide are to be ground. Predictions obtained from the theoretical analysis showed a correlation to results of practical experiments.

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