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# Plunge Cut Grinding Simplified: An Illustrative Student Experiment

By Dr. John Edward Wyatt and Dr. George J. Trembl

## Abstract

This paper will be of interest to industrial technology instructors, metal working operating personnel and researchers. It introduces a series of experiments that will help students understand the plunge-cut grinding process. These experiments can also be used for in-process monitoring to determine whether a grinding system is correctly set and is operating effectively.

The experiments concerned were undertaken at the University of the West of England (UWE), Bristol and are incorporated into the requirements for an undergraduate degree. The experiments were developed for a Jones & Shipman cylindrical grinder.

The students will have already taken a class explaining the basics of grinding. They then move to the laboratory. The in-class material is not included in this article. The areas that it pertains to are the construction of grinding wheels, safety, and the effects of speed and feed on a ground surface. The material also includes the dressing of a wheel and why it is important and the mathematics involved in the calculation of specific metal removal rates. The information regarding this may be found in manufacturing technology texts such as Kalpakjian & Schmid. The laboratory activity is described with typical results. It cannot be emphasized enough that safety must be given the utmost priority. Grinding wheels are one of the most dangerous tools in the metal working workshop and are prone to bursting, especially on start up. A qualified instructor/technician should always supervise each group.

## Introduction

Grinding was at one stage thought to be a secondary finishing process, used to provide a good surface finish and close dimensional & geometrical tolerances (Shaw 1996, Kalpakjian & Schmid 2005). However, with advances in grinding wheel and machine tool technologies, it has become a major machining operation. Techniques now exist such as creep feed grinding, and the new Rolls-Royce patented Very Impressive Performance Extreme Removal (VIPER). The latter is employed in the manufacture of turbine blades. Consequently, grinding techniques have become a very attractive material removal process. The VIPER technique can achieve removal rates of 300 mm<sup>3</sup>/min. This rate is five times faster than conventional creep feed grinding (Tyrolit 2003).

This paper is concerned with the plunge-cut grinding process. Here a cylindrical grinding operation reduces the diameter of a shaft by plunging the grinding wheel directly into the workpiece. Frequently, the wheel is not fed along the workpiece but is retracted, moved along and plunged in again. This operation is undertaken when the component is wider than the wheel. For this laboratory exercise, the workpiece is narrower than the wheel simplifying the set up. A simple process monitoring method is used that can be easily converted to a process monitoring system.

In most manufacturing operations, machining processes are set up with optimized speeds and feeds set by the operators following a company determined baseline for a particular job. The operator judges if these company set parameters can be adjusted to obtain an acceptable quality in a reduced pro-

cessing time. This is especially true for piecework. Should the operator leave the company such experience is lost. In addition, when components fall outside accepted tolerances, the remedy rests solely with the operator and not the company. This paper shows how simple information, when monitored and evaluated can gain much of the experience of the operator. It also describes how monitoring can help troubleshooting and gain improvements. Although there have been attempts to model the grinding process to optimize grinding operation parameters, (Zhu et al 1993) and to improve productivity (Lee et al 2003), an experimental approach such as that described is often preferred.

The exercise described was developed at UWE (Trmal et al 1996).

### Experimental Process

The information gathered during the above experiment was spindle head power and surface finish of the component. The machine was set up as shown in figure 1. Surface roughness was measured on a Talysurf stylus type surface roughness measuring instrument. The experiments involved the plunge-cut grinding of a steel workpiece manufactured from the UK equivalent of AISI 1141 in the cold-drawn state.

### Power Measurement

The measurement of grinding spindle head power provides extremely valuable information. It is readily obtained since the power transducer<sup>1</sup> concerned is unobtrusive and does not interfere with the grinding process. The measurement is directly related to the particular cutting process and the conditions that apply to the wheel and the machine tool settings. The power transducer measures the level of Watts that the spindle head motor pulls. This measurement is time based and there-

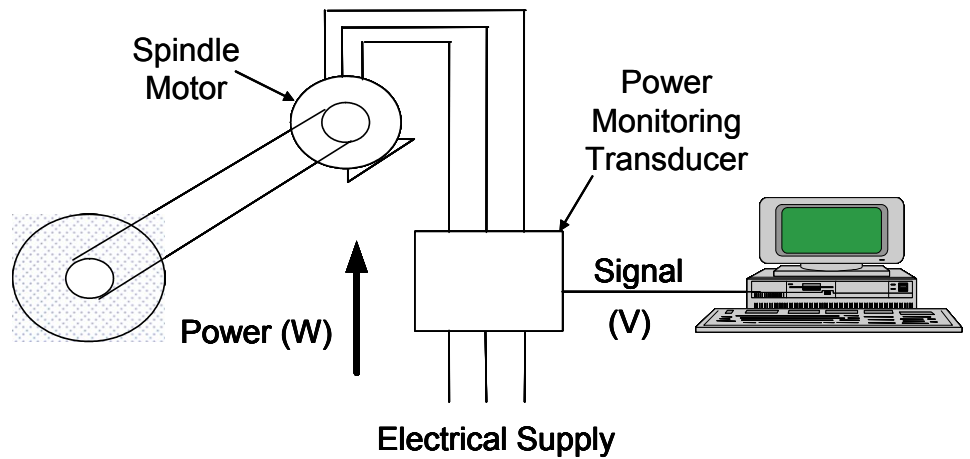


Figure 1. Experimental set up to monitor the plunge-cut grinding process

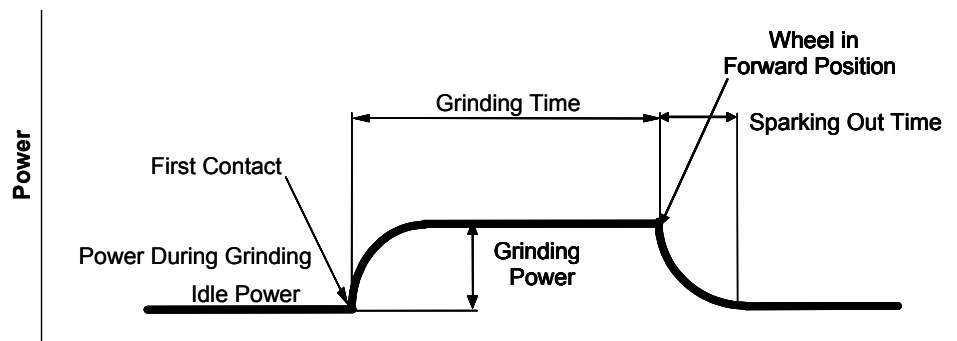


Figure 2. Predicted power consumption for the spindle head when plunge-cut grinding

fore allows for the whole operation to be monitored. The trace will initially show the increase in power when the wheel engages the workpiece. Secondly will exhibit a steady state where the diameter reduction is taking place. Finally, it shows the slow reduction in power, which indicated the time taken in sparking out the component<sup>2</sup>. The amount of power required to idle the wheel is also seen and this can be subtracted from the total power to determine the power used for the grinding operation. Figure 2 shows how power consumption for the plunge-cut grinding process can be divided into sections. It also describes what is involved in each section.

The time base provides much information, figure 2. If the total length of time to machine a component is known plus the reduction in radius of the workpiece, then the feedrate for that operation can be calculated as follows:

$$\text{Feedrate} = \frac{\text{Workpiece Radius Reduction}}{\text{Total Time to Grind Component}} \quad (1)$$

Where Feedrate(mm/s)  
 Radius Reduction (mm)  
 Time to Grind Component (s)

From this feedrate the Specific Removal Rate ( $Q'$ ) can be calculated from equation (2).

<sup>1</sup> Transducers that measure power (Watts) are readily available and are connected to the spindle motor input as per the manufacturer's recommendations. Their output can be measured using a computer as Watts measured is directly proportional to the voltage output of the transducer.

<sup>2</sup> Sparking out is the period of time that the grinding wheel is left in the fully advanced position to allow all of the material to be removed and to attain a high quality surface finish.

$$\text{SpecificRemovalRate} = \frac{\text{WorkpieceDiameter} \times \pi \times \text{Feedrate} \times \text{ComponentWidth}}{\text{WheelWidth}} \quad (2)$$

Where Specific Removal Rate (Q') (mm<sup>2</sup>/s)  
 Workpiece Diameter (mm)  
 Feedrate (mm/s)  
 Component Width (mm)  
 Wheel Width (mm)

The specific removal rate (Q') is the volume of material removed by every millimeter of the width of the grinding wheel every second as shown in figure 3. Note to enhance their understanding students must take the component and 'unwrap' it. The volume we are looking for is that removed from the component per second. This volume is the product of the circumference of the component, the feedrate as calculated in equation (1) and the component width. That volume is then divided by the wheel width to give the volume of material removed per millimeter of wheel width per second. Also note that because the volume is being divided by the wheel width the units are mm<sup>2</sup>/s. This is a source of confusion for many students as they see volumes in mm<sup>3</sup>. The instructor should emphasize this point.

The specific removal rate influences the amount of power that the spindle head motor draws, and this can be calculated from equation (3).

$$\text{GrindingPower} = \text{Specific Removal Rate} \times \text{Grinding Width} \times \text{Specific Energy} \quad (3)$$

Where: Specific removal rate (Q') has been determined above  
 Grinding width = Width of ground component (mm)  
 Specific energy = energy required to removal a unit volume of material (J/mm<sup>3</sup>)

From experience with grinding different materials, specific energy values can be calculated for any cutting condition. From this knowledge base, spe-

cific machines can be chosen for their spindle head power characteristics. Thus components can thus be assigned to a suitable machine and processed with optimum grinding parameters.

### Experimental Cases

The cases that are cited in this section are typical of the experimental situations that might arise in laboratory sessions. Figure 4 shows a typical power trace for a component that is 48.81 mm in diameter and has 0.7 mm removed from its diameter. The grinding width is 13mm. Apart from the component diameter, the other parameters mentioned remain the same for all of these tests.

### Example One

From figure 4 it can be seen that time for the cut to be made, excluding sparking out time is 18.27 seconds. Therefore, using equation (1) the feedrate can be calculated as 0.019 mm/s. from figure 3 the specific removal rate (Q') is calculated as shown in equation 4:

$$\begin{aligned} \text{Diameter} &= 48.81 \text{ mm} \quad (4) \\ Q' &= \text{Diameter} \times \pi \times \text{Feedrate} \\ Q' &= 153.34 \times 0.019 \\ Q' &= 2.94 \text{ mm}^2 / \text{s} \end{aligned}$$

Figure 3. Determination of specific removal rate when plunge-cut grinding

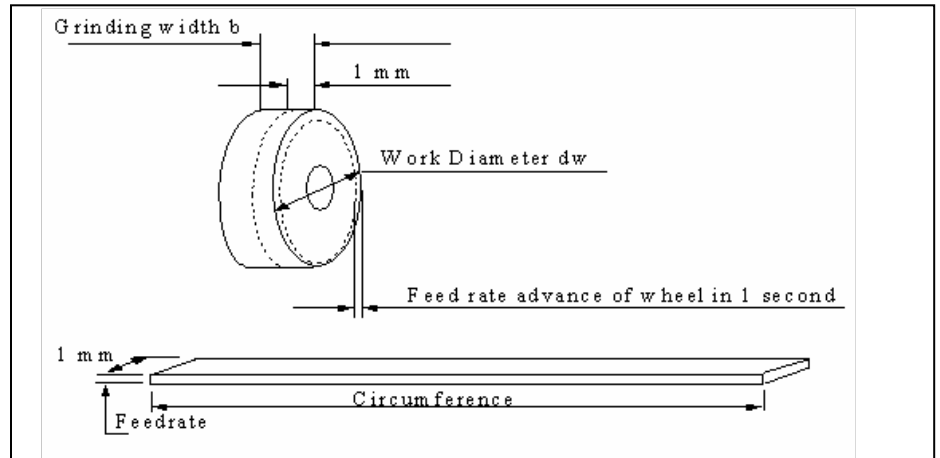
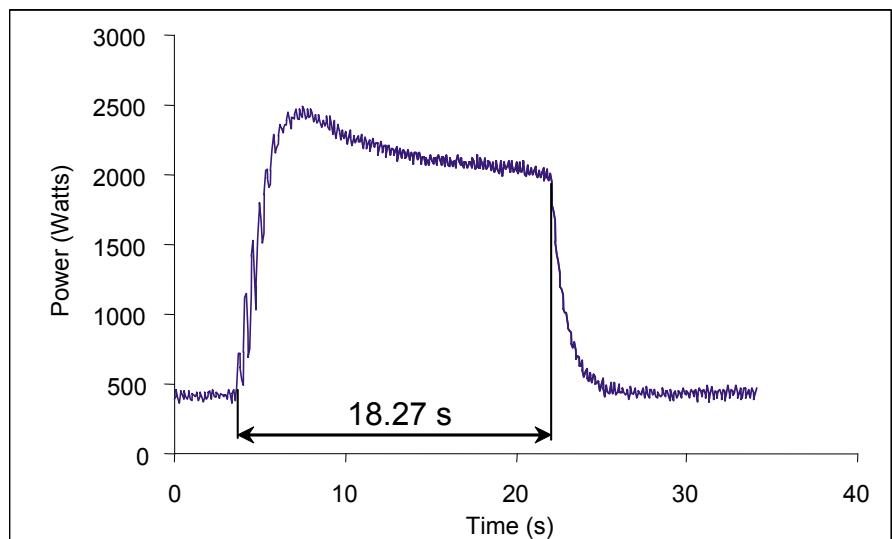


Figure 4. Example 1, A typical power trace from a laboratory test



<sup>3</sup> The dress lead is the feed of the diamond dressing tool as it passes across the face of the grinding wheel.

In addition, from figure 4 the average power utilized is 2184 Watts which when applied to equation (5) gives:

$$\text{Specific Energy (Es)} = \frac{\text{Average power}}{(Q') \times \text{Wheel Width}} \quad (5)$$

$$Es = 2184 / (2.94 \times 13)$$

$$Es = 2184 / 38.81$$

$$Es = 57.19 \text{ J/mm}^3$$

These figures are for wheel that has just been dressed. In addition, from figure 4 it can be seen that there is a sparking out period of approximately 5 seconds.

**Example Two**

Figure 5 shows another experiment with different cutting conditions i.e. a slower feedrate. The workpiece has a diameter 43.82mm a freshly dressed wheel was used, also.

The total grinding time for figure 5 is 33.24 seconds and thus, from equation (1) the feedrate is 0.01053 mm/s. Therefore, from figure 3, Q' can be calculated as follows (6):

$$\text{Diameter} = 43.82\text{mm} \quad (6)$$

$$Q' = \text{Diameter} \times \pi \times \text{Feedrate}$$

$$Q' = 137.664 \times 0.01053$$

$$Q' = 1.45\text{mm}^2 / \text{s}$$

From figure 5 the average power has been determined to be 1297 Watts. Thus the specific energy for this operation can be calculated from equation (7) as follows:

$$\text{Specific Energy (Es)} = \frac{\text{Average power}}{(Q') \times \text{Wheel Width}} \quad (7)$$

$$Es = 1297 / (1.45 \times 13)$$

$$Es = 1297 / 18.84$$

$$Es = 68.83\text{J/mm}^3$$

The sparking out time taken from figure 5 is also 5 seconds.

Both of these experiments had the wheel dressed to a depth of 12.5µm with a dress lead of 0.1 mm/rev, which

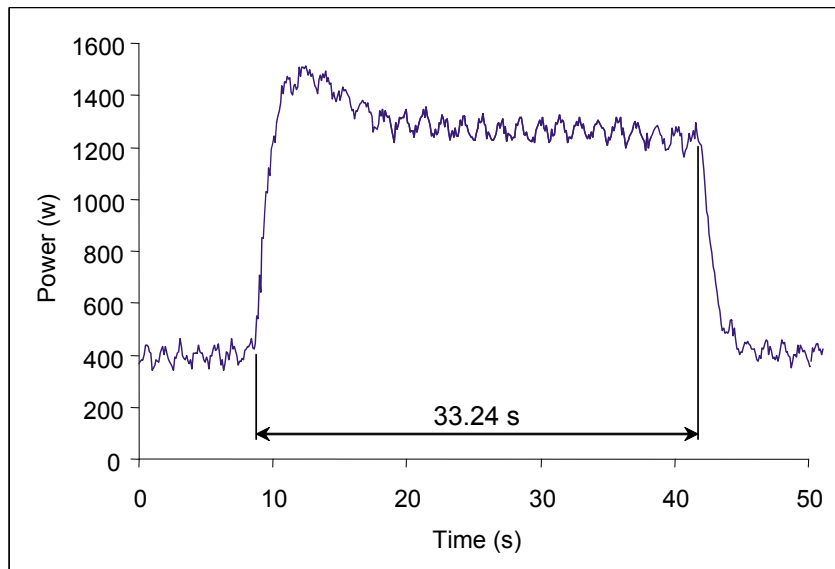
is a fine to medium dress lead<sup>3</sup>.

**Other Information Available**

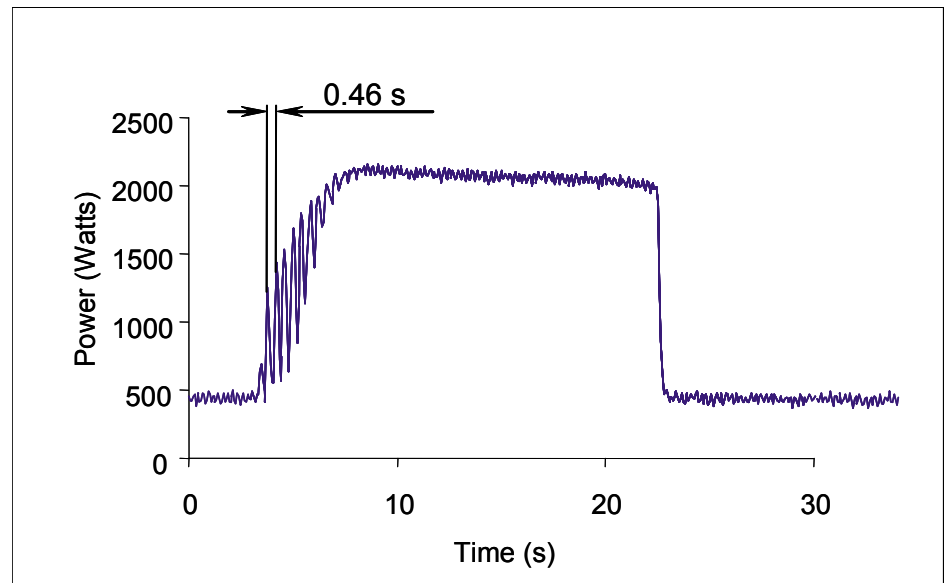
Other information can be obtained from the power monitoring trace. For example figure 6 shows a severe cyclic variation in power when the operation is at the grinding in stage. (See the beginning of the trace). This is due to initial eccentricity of the component. This lack of concentricity slowly

changes as the grinding wheel removes the high spot on the component. The wheel then machines the entire circumference where the power consumption becomes more steady. From this variation in power one can count the number of revolutions of the high spot over the time base and from equation (8) one can calculate the workpiece speed.

**Figure 5. Example 2, Another plunge-cut grinding experiment with a slower feedrate than example 1.**



**Figure 6. An example of how workpiece speed can be calculated through the component being out of round.**



$$v_w = \pi \times d_w \times n_w / 1000 \quad (8)$$

Where  $v_w$  = Workpiece speed (m/min)  
 $d_w$  = Diameter of the Workpiece (mm)  
 $n_w$  = Speed of workpiece (rpm)

From figure 6 there are 10 peaks in a time of 4.6 seconds, which equates to 2.17 revolutions per second, or 130 rpm. With a workpiece diameter of 48.81mm from equation 9 the workpiece speed can be calculated as:

$$\begin{aligned} v_w &= \pi \times d_w \times n_w / 1000 & (9) \\ v_w &= \pi \times 48.81 \times 130 / 1000 \\ v_w &= 20000 / 1000 \\ v_w &= 20 \text{ m / min} \end{aligned}$$

It can also be seen from figure 6 that this component was not sparked out when the grinding was completed. Furthermore, it can be seen that the power dropped off immediately and did not degrade as in the previous examples. This shows that the wheel was retracted directly after the component was ground to size. That is, it was not left to allow for sparking out. If the power trace degrades, then the wheel was still in contact with the workpiece for a set period of time until retraction.

A further piece of information obtainable from monitoring of spindle head power consumption, provides an indication of an incorrectly set machine or workpiece. Figure 7 shows that there is a major power spike when first contact between the workpiece and the wheel is made. This is due to the machine not being setup correctly, causing the wheel to hit the workpiece while still traveling under a rapid movement and not under controlled feed conditions. The amount of power drawn that is associated with the spike can be related to the elastic compliance of the total grinding machine, grinding wheel and component system.

### Surface Roughness Measurement and Evaluation

From the evaluation of surface roughness (Ra) values over a period of time,

an optimization of wheel dressing involved can be undertaken. This permits the wheel to be redressed before the component surface quality tolerance is compromised. This reduces the amount of rework/scrapage of components due to poor surface quality defects through wheel problems. From the two cases cited it can be seen that as the wheel wears the surface roughness (Ra) value starts to increase with the number of components machined, see figures 8 and 9 respectively.

It can be concluded from figures 8 and 9 that the Ra value in operations without the sparking out and dwell depends upon the specific removal rate. However, when sparking out is introduced into the process cycle the situation is different. There is no difference in the Ra value immediately after dressing at the beginning of the wheel life (Ra 0.6  $\mu\text{m}$ ). This indicates that identical wheel surfaces were generated by dressing. When the wheel wears, the surface roughness increases faster for operations with higher removal rates.

Figure 7. An example of how the power trace can detect an incorrectly set machine

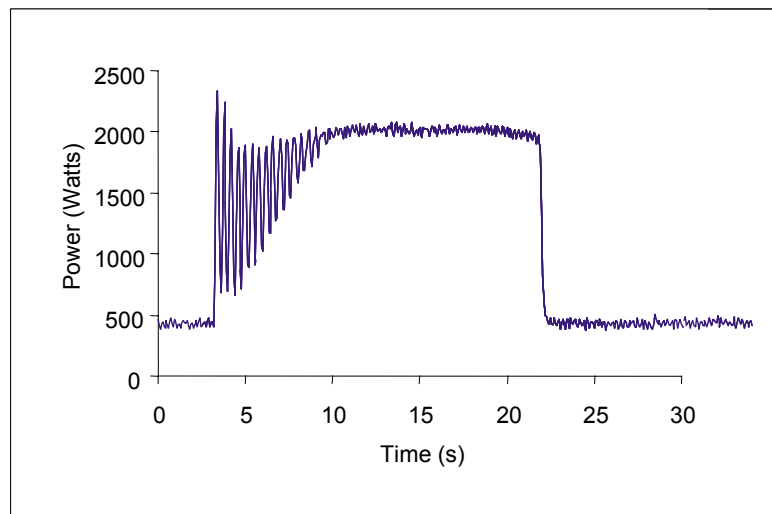
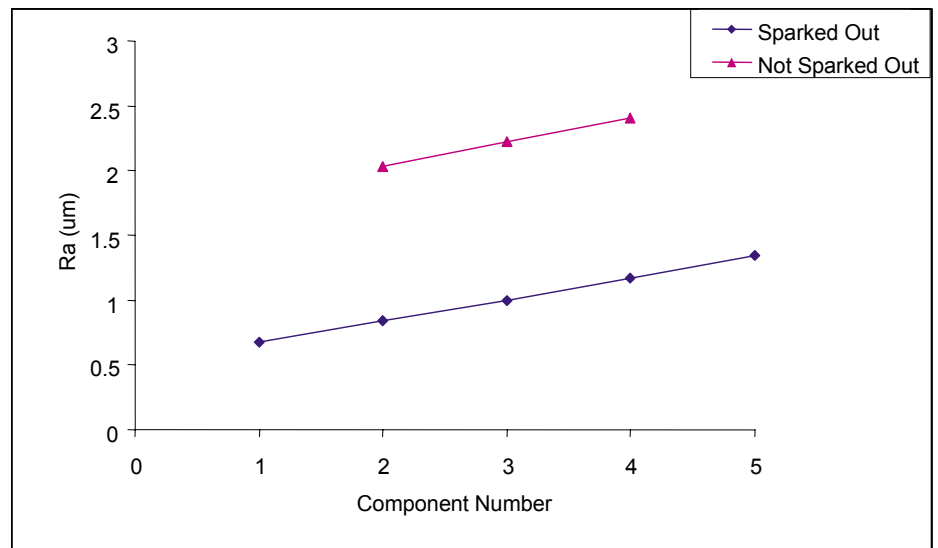


Figure 8. Ra versus number of components ground when machining to the parameters set for example 1 with  $Q' = 2.94 \text{ mm}^2/\text{s}$



The wheel surface is clearly changing more for higher removal rates where the forces are higher. Higher removal rates mean shorter cycle times but more frequent dressing will be required to maintain the surface finish.

A grinding wheel is a multi-point cutting tool but unlike a milling cutter, the points do not have a set geometry. Each point is an individual grit which is held in the bonding medium of the wheel. When a grinding wheel wears, the individual grits become flat and do not cut as efficiently as when they are sharp (Grinding Research Group 2003). Dressing the wheel breaks the flat/worn grits out of the bonding matrix exposing new sharp grits that can cut efficiently. Therefore, frequent dressing of the wheel permits a new cutting surface to be exposed. Thus helps improve both power consumption and surface finish.

The rate of deterioration of the surface roughness as a function of the removal rate and the time required for a dressing operation provide valuable data for optimizing the cycle.

### Conclusion

The laboratory exercises described have demonstrated that the use of a simple monitoring system can provide valuable data on the grinding process. The students can relate to theoretical concepts and use these in a “real world” scenario and consequently determine for themselves what variables affect the setting, operation and final component quality of a cylindrically ground component. This paper has also demonstrated that, via the use of simple, non-intrusive monitoring techniques, process monitoring presents acceptable method for acquiring archivable process experi-

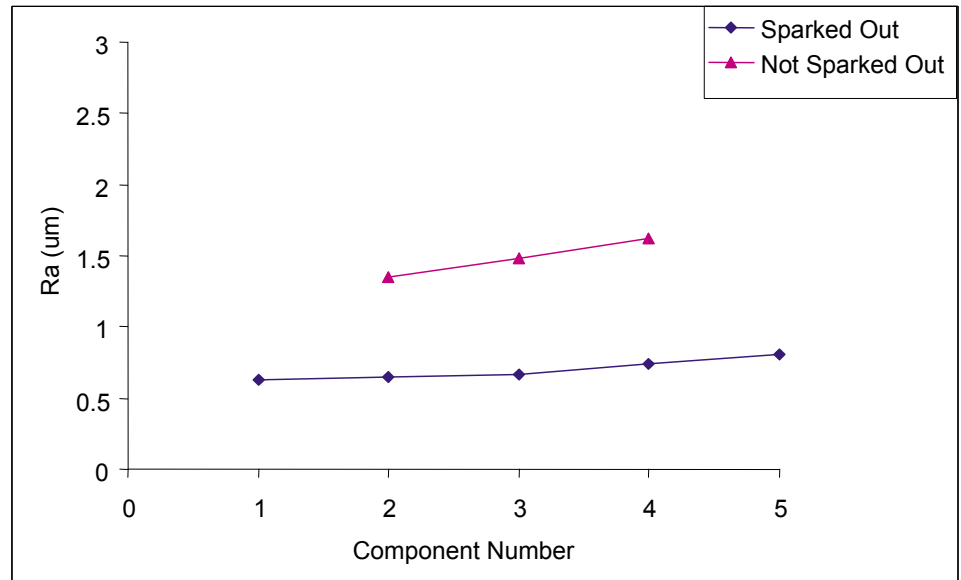


Figure 9. Ra versus number of components ground when machining to the parameters set for example 2 with  $Q' = 1.45 \text{ mm}^2/\text{s}$

ence. Thus the machining operation becomes a joint possession of the operator and the company, with the company retaining the operator’s experience even after he/she has left the company.

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