Process monitoring in high efficiency deep grinding- HEDG

A D L Batako and S Koppal
General Engineering Research Institute, Liverpool John Moores University, Byrom Street, Liverpool, L3 3AF, UK
E-mail: a.d.batako@ljmu.ac.uk

Abstract. High Efficiency Deep Grinding (HEDG) is an emerging technology that allows grinding to be undertaken at high wheelspeeds (up to 250 m/s), relatively large depth of cut (1 to 25 mm or more) and extremely high workspeeds up to 1000 mm/s. However, this new technology is not fully understood, thus it needs further investigation into machining requirements in order to develop adequate strategies to control the process. Various sensors are used to monitor the process performance in grinding. Thermocouple technique is commonly used and has advantages of low-cost, ease of use and direct surface temperature measurement. Temperature measurement is particularly challenging in deep grinding with cuts that may exceed 5 mm and high workspeeds approaching 1 m/s. Grinding coolant and electrical noise cause further challenges for achieving accurate and reliable temperature measurement. A single-pole thermocouple technique that provides reliable measurements is presented. This paper presents various grinding force measurement techniques and the thermal modelling that has been used to predict temperature in the HEDG process as a function of cutting parameters. Results obtained for in-process monitoring of the high efficiency deep grinding using the power and temperature measurements are presents.

1. Introduction
Manufacturing makes ever-increasing demands for higher machining speeds. This is particularly true in car and aircraft production but also for cutting tools. Parts such as high-speed cutting tools crankshafts, turbine blades and drill bits are all manufactured by grinding. Abrasive machining processes cover a great part (20-25%) [1] of all manufacturing processes. Grinding itself is partitioned into conventional shallow grinding, creep feed grinding and High Efficiency Deep Grinding (HEDG). Conventional shallow grinding employs moderate work speeds (0.5 to 300 mm/s) with small depths of cut typically 1 to 25 microns; whilst creep-feed grinding operates at very low workpiece speed (0.1 to 20 mm/s) with large depths of cut (1 to 25 mm).

High Efficiency Deep Grinding (HEDG), where it can be achieved, allows the grinding to be undertaken at high wheel speed (up to 250 m/s), relatively high depth of cut (1 to 25 mm or more) and extremely high work speed up to 1000 mm/s (950 mm/s achieved at Liverpool John Moores University, UK, on the newly developed experimental HEDG machine). HEDG combines the mechanics of high-speed grinding with creep-feed grinding and offers the possibility of achieving extremely efficient grinding with values of specific energy down to 6–7 J/mm³ and material removal rates exceeding 1000 mm³/mm.s. In contrast, in conventional shallow grinding and in creep-feed grinding, the specific grinding energy often exceeds 100 J/mm³ with much lower material removal...
rate. For example, in creep feed grinding of Nickel-based alloy the specific energy is 400 J/mm$^3$ for 150 mm$^3$ per mm width [2].

This new HEDG grinding process when correctly achieved, is capable of producing extremely high material removal rates exceeding – 1000 mm$^3$/mm/s without damaging the workpiece surface. However, the HEDG process is not fully understood and previous attempts at HEDG have been undertaken on non-specialised machine tools. Thus these attempts used lower to moderate machining parameters. In our recent work on HEDG, the initial industrial trials have doubled the productivity in crankshaft grinding for the automotive industry. This shows that HEDG is superior to existing grinding technologies, but the potential cannot be fully exploited at this time due to specific requirements for development of the machine tool and control strategies. HEDG process requirements differ from conventional grinding [3] and dictate a high power input and high machine tool stiffness.

In grinding, the grinding power is converted into heat. Therefore, to avoid high power consumption, high temperatures and workpiece damage, effective lubrication is critical. Lubrication is achieved by supplying a grinding fluid (coolant) into the contact zone between the grinding wheel and the workpiece. The main purposes of the coolant in grinding are to cool the workpiece and the wheel, to reduce wheel wear and to remove grinding swarf from the wheel and the cutting area.

With high material removal rates, high contact temperatures can become a serious problem even though specific energy is greatly reduced [4, 5]. In HEDG, deep cuts lead to large contact length (10 to 50 mm) and together with the high wheelspeed; it is difficult for the coolant to penetrate the entire grinding contact length. Therefore, it is found that HEDG is almost a dry grinding process. This results in high grinding contact temperatures [6] and high frictional forces which increase the wear of the wheel. To avoid workpiece damage caused by excessive heat in the grinding contact, temperature prediction based on power measurement [2, 4] is used to estimate maximum temperatures. In addition, actual temperature measurements using various techniques [7-9] are employed to validate the thermal models developed for HEDG. Fluid flow rates, pressures and actual flow through the grinding zone are measured to estimate the convection factors of the coolant. The coolant delivery rates and pressures are also measured. The acoustic emission sensor in Figure 1 was used to calculate the actual workspeed which often differs from the value in the CNC. Generally in grinding, the acoustic emission is used for touch dressing, gap elimination and collision avoidance. Recent research has shown that it is possible to extract the burn temperatures characteristics from the acoustic emission signal [10].

2. Measurements in Grinding.

The HEDG process is not fully understood and most previous attempts at HEDG have been undertaken on non-specialised machine tools. Thus these attempts used lower to moderate machining parameters. Liverpool John Moores University has developed a the first HEDG grinding machine that provides wheelspeeds up to 145 m/s and workspeeds up to 3.3 m/s, with large depth of cuts and material removal rate exceeding 1000 mm$^3$/mm.s. Figure 1 (left) is the general view of the HEDG and on the right hand side is a diagrammatic illustration of the measurements flow in the system. Up to seven parameters are measured simultaneously using a data acquisition system capable of sampling at 5MS/s. These parameters are: temperature in the grinding zone, differential pressure in the hydrostatic bearings, power, workspeed, tangential grinding force and acoustic emission. The coolant delivery rates and pressure are also measured. The acoustic emission sensor in Figure 1 was used to calculate the actual workspeed which often differs from the value in the CNC. Generally in grinding, the acoustic emission is used for touch dressing, gap elimination and collision avoidance. Recent research has shown that it is possible to extract the burn temperatures characteristics from the acoustic emission signal [10].
2.1. Force Measurements

The efficiency of a grinding process is characterised by the energy consumed per unit volume of material removed. The grinding efficiency can be estimated by measuring the forces or the power. Force measurements are used to estimate the net power consumed by the grinding process. In direct power measurement it is necessary to subtract the no-load power from the measured value to obtain the net grinding power (see Figure 6). The no-load power is the power needed to spin the grinding wheel to a given rev/min plus the extra power consumed due the application of the coolant) the net grinding power is the actual energy spent during the grinding. Four methods were used to measure the grinding force in HEDG. The differential pressure in the pads of the hydrostatic bearing was measured using high performance pressure transducers; Figure 2 left shows a picture of the sensors on the HEDG machine whereas Figure 2 right is the sketch of the connections between the pads of the bearing. This method required rigorous calibration to obtain accurate force reading and can be used in both surface and cylindrical grinding.

A typical force measurement in surface grinding is illustrated in Figure 3 left where the workpiece is mounted on a 3-axis dynamometer. This figure shows a thermocouple connection for temperature measurement and an acoustic emission sensor for exact determination of the workspeed as the latter affects the calculated material removal rates. A system was devised to calibrate the measurement of the tangential grinding force by recording the current supplied to the linear motor. The main spindle power was measured as reference point to the above measurements. The obtained results were in a good agreement. However the force measurement using pressure sensors had a small limitation. The output of the sensors was sensitive to the grinding depth of cut, with a threshold of 1mm, below which the pressure reading was extremely noisy. All these measurements were used to accurately calculate the specific grinding energy (SGE), which is a standard measure in industrial practice. HEDG is a new technology thus it requires full process characterisation for industrial implementation that is why it is necessary to explore the above measuring techniques to find the most suitable.
Measurements of spindle power and the material removed allowed defining the specific grinding energy for different materials and process configurations. Figure 3 right demonstrates that the specific energy approaches 6 J/mm³ in grinding cast iron (CI) in HEDG regime.

2.2. Temperature Measurement in HEDG

In the investigation of grinding process, temperature measurement is employed to estimate the actual temperatures in the grinding zone. The various techniques used to measure are explored in [7-8]. Standard thermocouples are inserted into a hole drilled beneath the grinding surface. This method provides acceptable results, however, the reading not direct and need extrapolating up to the ground surface.

Single-pole thermocouple is made of a strip of a conducting metal (constantan in this study) that is inserted in split workpiece. The second pole of the thermocouple is the workpiece. Figure 4 left show a typical arrangement of a single-pole thermocouple. The measuring junction is formed in real-time during the grinding process as illustrated in Figure 4 right. The single-pole thermocouple can be ground at any level thus it allows measuring actual grinding contact temperature which is a great advantage over standard due to large depth of cuts in HEDG.

Single-pole thermocouples have a very low signal to noise ratio especially in the presence of coolant and high frequency inverters. However, by taking a series of precaution it is possible to develop a reliable temperature signal extraction system. In this investigation a zero-shift filtering technique [7] was used to recover the grinding temperature signal. Figure 5 left illustrates the output of the temperature measurement system with a single-pole thermocouple using a software filtering with zero-shift. Figure 5 right is the result of a series of actual grinding temperatures measured (Tmax msd) in the HEDG process alongside with the predicted values (Tmax dry, Tmax wet) using the theoretical thermal modelling in [4-5]. It is observed that the actual measured temperatures are close to the predicted values for dry grinding which indicates a coolant burnout in the contact zone. These results are in agreement with the statement that HEGD is almost a dry grinding process.
3. Control Strategy for HEDG process

Generally in manufacturing, it is desirable to have control strategies for each type of process. In grinding, thermal modelling is used to forecast the temperatures in the contact zone. The models [4-5] use the grinding power to calculate expected temperature rise in the workpiece, which is then validated using measured temperatures as shown in Figure 5 left.

The control strategy developed in this investigation operates on the basis that the total power consumed by the grinding process is fully converted into heat. The generated heat is partitioned between the workpiece \( (q_w) \), the wheel \( (q_s) \), the chip \( (q_{ch}) \) and the coolant \( (q_f) \).

The total heat flux \( (q_t) \) is the net grinding power \( P \) per unit contact area \((b.l_c)\); where \( b \) is the grinding width and \( l_c \) is the contact length.

\[
q_t = \frac{P}{b\cdot l_c} = q_w + q_s + q_{ch} + q_f
\]  

(1)

The heat transferred into the workpiece and into the chip is expressed in terms of the maximum temperature in the contact zone as follows:

\[
q_w = \frac{\beta_w \cdot (l_c - T_{min})}{C \cdot \sqrt{v_w}} \quad q_{ch} = e_{ch} \cdot a_{ch} \cdot \frac{v}{l_c}
\]  

(2)

\( C \) is a factor depending on Peclet number [4-5], \( v_w \) is the workspeed and \( \beta_w \) is the thermal property of the work material. The temperature of the chip rises to a value close to the melting point temperature \( (T_{mp}) \), which is estimated as 1250°C. The specific chip energy is define as \( e_{ch} = \rho \cdot c \cdot T_{mp} \) where \( \rho \) is the...
density and \(c\) is the specific heat capacity of the workpiece material. The maximum temperature \(T_{\text{max}}\) in the grinding zone is calculated from the values of convection factors and eq.1 as

\[
T_{\text{max}} = \frac{q_w - q_{ch}}{h_w + h_f} R_{ws}
\]  

(3)

Where \(h_w\) and \(h_f\) are convection factors for the fluid and workpiece respectively; \(R_{ws}\) is the partition ratio between the workpiece and the wheel that depends on cutting wear flats, \([4]\).

Figure 6 left depicts the flow chart of the algorithm used for the control strategy and Figure 6 right is the front panel of the control system, which was developed in Labview. This is an open loop advisory system that supports the operator to avoid workpiece damage due to high temperature. The operator sets the grinding parameters i.e. workpiece material, workspeed, wheel material, wheel diameter, wheelspeed, the depth of cut and coolant type. A single-pole thermocouple inserted into the workpiece reads the temperature and a power sensor provides the actual grinding power in real-time. The system runs continuously and immediately after each grinding the system provides the operator with the temperatures of the process. If a desirable temperature limit was given the system would flag a red light if the actual grinding temperature exceeded the limit value.

4. Conclusions
The rigorous study of various measurement techniques has allowed for the development of a control strategy for the HEDG process. It was found that the developed system for temperature measurement using a single-pole thermocouple provides accurate reading and was simple to use due to its ability to be ground together with the workpiece. The control strategy operating in real-time based on power and measured temperature has shown to be a good tool to assist in grinding operations. It is planned to further develop the system to include coolant delivery monitoring with the capability to advise the operator on best machining configuration based on historical database.

References
[1] S. Malkin, Grinding Technology: Theory and Applications of Machining with Abrasives, Wiley, New York, 1989.
[2] Marinescu I D, Rowe W B, Dnimitrov B, Inassaki I, (2005); Tribology of abrasive machining processes.
[3] Morgan M N, Rowe, W B, Batako A, 2003, Energy limitation in HEDG and Conventional Grinding; 6th International Symposium on Advances in Abrasive Technology, ISAAT.
[4] Rowe W B, (2000), Thermal analysis of high efficiency deep grinding, Int. Journal of machine tool and manufacture, 41, 1-19.
[5] Rowe W B, Morgan M N, Batako A, Jin T, (2003); Energy and Temperature Analysis in Grinding, Keynote Paper, 6th Int. LAMDAMAP Conf. and Exhibition on Laser Metrology, Machine Tool CMM and Robot Performance, Laser Metrology and Machine Performance 2003 VI, 3-23.
[6] Jin T, Stephenson D J, Corbett J, (2002); Burn threshold of high carbon steel in High Efficiency Deep Grinding, Proc I Mech E, Part B Journal of Engineering Manufacture, 216: 357-364
[7] Batako A D, Rowe, W B, Morgan M N, (2005); Temperature measurement in High Efficiency Deep Grinding, Int. Journal of machine tool and manufacture, 45, 11, 1231-1245
[8] Batako A D L, Rowe, W B, Morgan M N, O Mgaloblishvili, (2005); High-speed temperature measurement in grinding using single pole thermocouples, CIRP 2005 conf. Antalya, Turkey; invited presentation.
[9] Chen X, Griffin J, Liu Q, (2006), Mechanical and thermal behaviours of grinding acoustic emission, Int. Journal of Manufacturing Technology and Management (in press)