Performance Analysis of Cylindrical Grinding Process with a Portable Diagnostic Tool

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Abstract

This paper presents an approach to develop a diagnostic tool that can monitor the power drawn by the spindle motor using a power sensor and infeed of grinding wheel using a linear variable differential transformer (LVDT) in cylindrical grinding machine. A combination of spindle power and wheel infeed measurement enables the performance evaluation of grinding process. This evaluation suggests the possibility of optimizing the grinding cycle in order to enhance the efficiency of grinding process. The effectiveness of the developed in-process, portable diagnostic tool is demonstrated with a case study.

Keywords: Diagnostic system, Process monitoring, Power measurement, Optimization

1 Introduction

Grinding process plays a major role in controlling the quality requirements of components in terms of dimension, form, finish and surface integrity. Apart from these requirements, the cycle-time and grinding costs are also considered as important for assessing the effectiveness of grinding. In brief, the entire grinding process can be viewed as an input-transformation-output system [Tönshoff (2002), Subramanian (1992)]. The inputs to the process include grinding machine tool, process parameters, work material properties, and tooling. On the other hand, the output of the process deals with technical and system outputs. Form, dimensions, finish and integrity on part are the technical outputs while the productivity i.e. grinding cycle time and the cost of grinding are the system outputs. The performance of any grinding process can be enhanced by enhancing both technical and system outputs. Based on the work material and its geometry, the type of grinding wheel and the conditions of grinding are selected to realize the desired technical outputs [Subramanian, 1995].

During grinding, the interaction between the abrasive grain and the work-piece results in material removal process. As this interaction is highly complex, it is difficult to realize consistent results in grinding [Subramanian, (1992), Malkin and Guo (2008)]. Only when the behaviour of grinding process is completely understood and is represented with suitable models, then it will be possible to analyse the process consistency and its performance enhancement. Thus, this demands for a system that can continuously monitor the grinding process and suggest suitable measures for enhancing the process outputs.

Attempts made on monitoring of grinding process include the monitoring of process variables with different types of sensors such as force, acoustic emission, temperature, pressure and power [Tönshoff et. al., 2002]. An attempt was made to monitor the forces in cylindrical grinding by means of a non-contact displacement sensor embedded in aerostatic spindles. This particular type of force monitoring turns out to be quite complex and expensive due to certain difficulties in direct monitoring of force [Eric et. al., 2005]. In contrast to this, the power drawn during grinding is much easier to measure but not fully explored [Inasaki et. al. (2000), David and John (2003), Wei Tian (2009)]. Hence, it is appropriate to think of a compact, portable diagnostic tool with power sensor for on-line monitoring of the process. This sensor combined with infeed displacement sensor can analyse the performance of abrasive wheel in grinding.

2 Approach for Process diagnosis

Generally, any process diagnostic system initially collects the data with a suitable set of sensors, and then analyses the collected data to indicate the status of the process. In case of grinding, the data collected from a set of sensors can be used to analyze the relevance of grinding cycle and for estimating the performance of grinding process [Andrew et. al., 2006]. Therefore, the steps covered to diagnose a grinding process include: i) Process monitoring and data acquisition, ii) data analysis dealing with feature recognition and feature evaluation, and iii) Inferences to suggest process enhancement strategies. Figure 1 shows a schematic diagram illustrating the steps
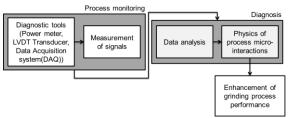
involved in monitoring and diagnosis of grinding process.

Figure 1 A Schematic of grinding process monitored with diagnostic tool

2.1 Diagnostic tools

Figure 2 shows the arrangement of powercell to monitor the power drawn by spindle motor and LVDT to measure the infeed of wheel head during grinding of a component in a cylindrical grinding machine.
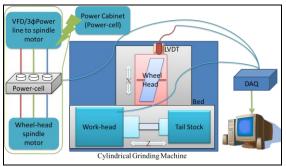

Figure 2 Schematic of a diagnostic tool showing the arrangement of sensors in a cylindrical grinding machine

2.2 Measurement of spindle motor power

During grinding of a component, the power drawn by wheel spindle motor is monitored with a powercell connected to the spindle motor input power line. In the power cell, Hall-effect sensor measures the current and a bypass internal circuitry samples the voltage simultaneously. A vector multiplication of measured current and voltage including the power factor enables the measurement of effective power drawn by the spindle motor. Figure 3(a) shows the position of powercell in the electrical cabin of machine tool during measurement.
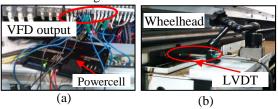

Figure 3 Location of a) Powercell and b) LVDT in grinding machine tool

2.3 Measurement of infeed movement of wheel head

Figure 3(b) shows the location of LVDT on the bed. This transducer is held in a mount with a magnetic base that provides a fixed reference point on bed. The plunger of LVDT senses the feed movement of entire wheel head during plunge grinding of component.

2.4 Acquisition and Analysis of data collected with the sensors of a diagnostic tool

The output of powercell and LVDT are analog signals and are converted into digital form with data acquisition (DAQ) unit. This particular data is then analyzed using LabVIEW software. Figure 4 shows a typical signal captured using powercell and LVDT connected to the grinding machine. This signal represents the signature of grinding process while grinding the component [Wei Tian, 2009].
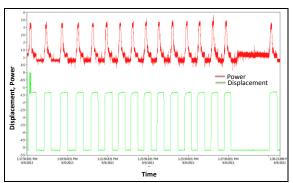

Figure 4 Typical signature of plunge grinding process with Power and LVDT sensors

2.5 Characterization of grinding cycle

Figure 5 shows the overlapped power and displacement signals measured during each grinding cycle of a component. It clearly shows the variation of power and wheel infeed at different stages i.e. roughing, semi-finishing, finishing and spark-out, in a typical grinding cycle chosen for plunge grinding of a component and are numbered as 3, 4, 5, and 6. From the variation of power in different stages of grinding, it is evident that the power drawn by spindle motor during roughing stage is higher due to higher rate as well as the magnitude of infeed of wheel into work. In contrast to this, semi-finishing and finishing stages employing smaller magnitude of infeed with reduced infeed rate resulted in lower power, as shown in Figure 5. During spark-out, the power drawn by motor is very less and in most cases slightly above the power drawn during idle running of motor. The data collected during the grinding of components can be utilized to evaluate the process stability over a period time. Any substantial change in the trends or variation of power in different stages of grinding cycle can aid in identifying the status of grinding wheel such as sharp, worn out or glazed and also aid in assessing effect of dressing conditions, changes in the coolant application, etc.
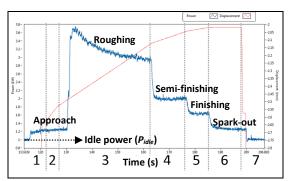
Figure 5 A typical grinding cycle

2.6 Signal analysis and inferences

The variation of power in different stages of a grinding cycle over a period leads to direct inferences about the drift in grinding process behaviour. Figure 6 presents the power signal monitored over 'n' number of cycles. During grinding, the wheel undergoes changes such as grit wear, fracture of bond, loading of chips into pores due to which the power shows an upward trend due to the increase of forces in grinding. This can be seen in cycle '1' to cycle 'n'. Analysis of these plots will indicate the status of grinding as well as grinding wheel.
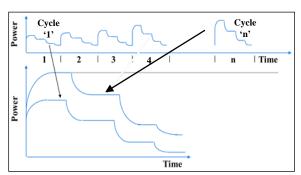

Figure 6 Superimposition of signals

2.7 Power and other derived units

Previous discussion on the trends of power variation with time gave an indication about the status of grinding process. As the diagnostic tool monitors both power and infeed of wheel, these trends can be further analyzed to derive some quantitative metrics in assessing the condition of grinding process. Grinding power is an indicator of the rate of energy consumption for material removal process and has a direct relationship with material removal rate (MRR) (Q_w). The MRR for a grinding cycle can be estimated by using the process parameters such as work velocity (V_w), depth of cut (a_e) and grinding width (b_w). The infeed measured with LVDT over a grinding cycle can be used to estimate the variation of MRR as shown in Figure 7. This variation of MRR along with power can be used to derive the specific cutting energy (U_c) during grinding of a component.

$$U_c = [(P_c)/Q_w] \qquad (1)$$

Where, P_c is the cutting power required for material removal during grinding. Powercell measures the absolute value of power that includes idle running power of spindle motor (P_{idle}) and grinding power (P) required for grinding of components through various stages of grinding cycle. This grinding power is given by the relation,

$$P = P_{th} + P_c \qquad (2)$$

Where, P_{th} – Threshold power, i.e. the power required to initiate the grinding process
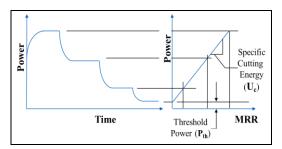

Figure 7 Relation between Power and MRR

The effect of friction due to abrasive grain sliding and the rubbing of bond against the work material, results in the threshold power (P_{th}). The influence of P_{th} decreases as MRR increases and thus results in lower specific energy in grinding at higher MRR.

The specific cutting energy depends on the equivalent chip thickness (h_{eq}), analogous with any machining process. Thus, U_c depends on the depth of cut during grinding. In grinding, the thickness of chip can be controlled by varying grinding process parameters or by changing the wheel characteristics with varying dressing conditions. With fine dressing condition i.e. less dressing depth and low dressing traverse rate, the wheel surface is less damaged resulting in fine topography on wheel surface. Such surface on wheel can lead to less chip space and can result in more chip friction, though the chip size remains same. This is reflected in the increased grinding power drawn by spindle motor. With coarse dressing condition, severe bond rupture occurs resulting in rougher wheel surface and better abrasive grit protrusion. This produces larger chip space and hence results in less chip friction. However, such a wheel surface generates poor finish with lower specific grinding energy [Subramanian, 1995]. Therefore, the measurement of power and infeed of wheel can aid one to assess the condition of wheel from time to time and the choice of suitable conditions for dressing to generate the desired topography on wheel surface.

2.8 Performance analysis of grinding process with diagnostic tool

The effectiveness of diagnostic tool in assessing the performance of the grinding process is demonstrated by means of experimental trials in cylindrical grinding. Table 1 presents the details of machine, grinding wheel, dresser and conditions of

grinding employed for the experiments. A hollow cylindrical component, mounted on a mandrel was held in between the centers during grinding.

Table 1 Process settings used in plunge grinding

Machine Tool	Angular wheelhead CNC
Work-material	D2 steel (60 HRC)
Wheel spec	A 80 J 5 V
Dresser spec	Blade type
Coolant type	Emulsion type (4%)
Operation	Cylindrical plunge grinding
Wheel speed	45 m/s
Work speed	26 m/min
Grinding length	10 mm

Table 2 Dressing condition

Case	Infeed [on dia] (mm)	Dressing overlap ratio	Passes
Fine	0.015	12	2
Coarse	0.040	6	2

Table 3 Grinding cycle details

Step	Stock removal [on dia] (mm)	Infeed rate [radial] (mm/min)	Material removal rate MRR (mm^3/s)
Roughing	0.80	0.66	40.0
Semi-finishing	0.15	0.33	20.0
Finishing	0.05	0.16	10.0
Spark-out	15 revolutions		

Experimental trials considered the wheel dressed with two different dressing conditions, shown in Table 2, but employed the same grinding cycle, shown in Table 3, for grinding of components of same geometry. This particular choice is made since the dressing conditions change the topography on wheel surface and thus affects the performance of wheel in grinding. By monitoring the power and wheel infeed with diagnostic tool, the specific energy in grinding, using the wheel dressed by fine and coarse dressing can be determined.

Figure 8(a) shows the variation of power in different stages of grinding cycle employed while grinding of components with the wheel dressed by fine and coarse dressing. In both cases, the grinding cycle chosen for grinding of components is the same. This can be seen from the plot showing the same variation of infeed during the grinding cycle. The power drawn by the spindle motor in different stages of grinding cycle clearly shows that the power is higher in the grinding cycle with fine dressed wheel.

Figure 8(b) presents the variation of power with material removal rate (MRR) in different stages of grinding. This clearly indicates the maximum power with large material removal rate during roughing

stage. Using the data obtained with the diagnostic tool, the threshold power and specific energy in grinding are estimated, and are presented in Table 4. The threshold power (P_{th}) is same for both the dressing conditions, while the specific grinding energy (U) increases with the decreasing material removal rate as the grinding progresses from roughing to finishing stage.
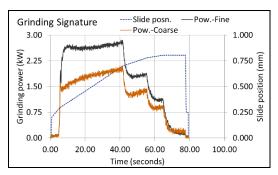

Figure 8(a) Variation of power during grinding cycle using wheel dressed with different dressing
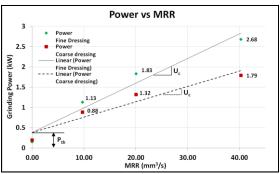

Figure 8(b) Variation of power with MRR during grinding using wheel dressed with different dressing conditions.

Table 4 Derived Specific energy, threshold power and finish measured in grinding using fine and coarse dressed wheel

	Grinding cycle stage	MRR [mm^3/s]	Dressing condition	
			Fine	Coarse
Specific Grinding energy [U] [J/mm^3]	Roughing	40	69	50
	Semi-finishing	20	50	73
	Finishing	10	110	90
Specific cutting energy (U_c) [J/mm^3]			62	38
Threshold power (P_{th}) [W]			370	370
Surface Roughness [R_a]			0.32	0.56
Surface Roughness [R_z]			2.30	3.50

Figure 8(b) shows increase in grinding power for finer dressed wheel. As discussed earlier, fine dressing conditions results in smoother wheel surface and results in more chip friction during grinding. On

the other hand, the rougher surface produced by coarse grinding results in lesser grinding power. In addition, the specific cutting energy (U_c) during grinding with fine dressed wheel is higher compared to coarse dressed wheel. The higher Uc may be due to the lesser chip space formed due to fine dressing conditions, resulting in more chip friction.

To confirm the nature of surface produced on the ground component by the wheel dressed with different conditions of dressing, the surface finish on the ground component is measured with a stylus type roughness measuring instrument and the results are shown in Table 4. From these results, it is observed that the wheel with finer dressing produced a smooth surface in contrast to a rough surface by coarse dressed wheel. Thus, the fine dressing of wheel results in a closed wheel surface morphology, which lead to the higher specific cutting energy (U_c) together with the finer surface finish after grinding with the wheel, as clearly evident from the results.

From this study, it is evident that the measurement of grinding power and wheel infeed using a portable diagnostic tool enables one to study the details of the grinding process as practiced in an industrial shop floor. Such in-depth understanding of the process aids to refine the research approaches inline with industrial practices. Thus, portable diagnostic tool helps to study the performance of grinding process with more scientific approach creating a synergy between academic research and industrial practices and their immediate extension to industrial applications helps to advance the state of the art in precision manufacturing.

3 Conclusion

This paper covered the development and application of a portable, in-process diagnostic tool for monitoring of grinding power and wheel infeed during cylindrical grinding, using a powercell and LVDT. The collected data is then used to evaluate the performance of the grinding process in terms of specific energy consumption in grinding. Future efforts are directed towards using this diagnostic tool for designing efficient grinding cycles for optimal use of grinding machines.

4 Acknowledgements

References

Andrew K.S. Jardine, Daming Lin, Dragan Banjevic (2006), 'A review on machinery diagnostics and prognostics implementing condition-based maintenance', Mechanical Systems and Signal Processing, Volume 20, Issue 7, 1483-1510.

B. Karpuschewski, M. Wehmeier, I. Inasaki (2000), 'Grinding Monitoring System Based on Power and Acoustic Emission Sensors', CIRP Annals - Manufacturing Technology, Volume 49, Issue 1, 235-240.

David Graham and John A. Webster (2003), 'A practical, portable hardware/software system monitors and records creepfeed grinding's "vital signs" to minimize thermal damage', System takes grinding's temperature - American machinist, Dec 2003.

Jeremiah A. Couey, Eric R. Marsh, Byron R. Knapp, R. Ryan Vallance (2005), 'Monitoring force in precision cylindrical grinding', Precision Engineering, Volume 29, Issue 3, 307-314.

H.K. Tönshoff, T. Friemuth, J.C. Becker (2002), 'Process Monitoring in Grinding', CIRP Annals - Manufacturing Technology, Volume 51, Issue 2, 551-557.

K. Subramanian (1999), 'Measurement and Analysis of Grinding Processes', Abrasives Magazine, April, May 1999.

K. Subramanian (1995), 'Finishing Methods Using Multiple or Random cutting Edges', Section 3C, Vol. 5, Surface Engineering, published by the American Society for Materials.

K. Subramanian and R.P. Lindsay (1992), 'A Systems Approach for the Use of Vitrified Bonded Superabrasive Wheels for Precision Production Grinding', ASME Transactions, Journal of Engineering for Industry, Vol. 114, 41-52.

Stephen Malkin and Changsheng Guo (2008), 'Grinding Technology: Theory and Application of Machining with Abrasives – 2nd edition', Chapter 5 - Grinding mechanisms, Industrial press, New York.

Wei Tian (2009), 'Signature analysis of OD grinding processes with applications in monitoring and diagnosis', MS thesis, Worcester Polytechnic Institute.