Strategies for a Generic Intelligent Control System for Grinding
Part 1: Development

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ABSTRACT

A generic intelligent control system (GICS) has been developed on a personal computer and is capable of being implemented with a range of commercially available CNC grinding machines to carry out intelligent grinding control. Intelligent strategies play an important role in the generic intelligent control system. This paper discusses the control strategies incorporated into the GICS and the development based on models of the grinding processes.

NOMENCLATURE

a	depth of cut
b	grinding width
c_1, c_2, c_3	coefficients in power equation
c_g	specific heat capacity of the abrasive grains
c_w	specific heat capacity of the workpiece
C	heat flux distribution constant
d_e	equivalent diameter of grinding wheel
d_s	grinding wheel diameter
d_w	workpiece diameter
e_c	specific energy
e_c^*	critical specific energy
k	convergence coefficient
l_e	effective contact length
l_g	geometrical contact length
n	number of data points
n_s	grinding wheel rotational speed
P	theoretical grinding power
P	measured grinding power
P_{target}	target grinding power
r_o	grain contact radius
R_w	fraction of the total energy partitioned to the workpiece
t	time
T_d	dwell time
T_i	infeed time
v_f	infeedrate
v_{fnew}	updated value of the infeedrate
v_{fold}	currently used value of the infeedrate
v_s	wheel speed
v_w	workspeed
X	actual infeed position
X_c	commanded infeed position
Xd	stock removed during dwell period
X_i	stock removal during infeed
X_{os}	overshoot position
X_p	programmed infeed position
X_t	total stock removed
θ^*_m	critical temperature
α_g	grain thermal diffusivity
κ_g	grain thermal conductivity
κ_w	workpiece thermal conductivity
ρ_g	grain density
ρ_w	workpiece density
ΔX	steady state error (deflection before dwell start)
Δt	time interval between two samplings
τ	time constant
ζ	dimensionless time (thermal model)
$\Phi(\zeta)$	transient time function

1 Introduction

The generic intelligent control system (GICS) is designed to control a range of grinding processes using a group of selectable adaptive strategies. The GICS is based on a PC platform and is capable of being integrated with a range of CNC grinding machines. The GICS can be configured to control a user specified grinding process by interacting between the user and the system executor. The configuration routine generates a pointer to a specific control routine which satisfies the requirements proposed by the user. A control routine consists of calculations and rules for decision making.

The aims of intelligent control are to achieve size, roughness and shape of the workpiece within tolerance and within the minimum average cycle time. Other possibilities are to minimise set-up time and provide initial selection of grinding conditions. This paper discusses some basic principles of intelligent control and the development of algorithms to provide the generic intelligent control system.

The grains on the surface of a grinding wheel usually have negative flank angles and many also have significant wear flats. When a workpiece is ground, a number of grains cut the workpiece simultaneously and a significant normal grinding force is generated by the action of the grains penetrating the surface of the workpiece. Under the effect of the normal grinding force, the grinding wheel is deflected away from the workpiece. The deflection makes it difficult to control workpiece size to a high order of accuracy since there is a difference between the programmed infeed position and the actual infeed position. In order to achieve the correct workpiece size and roundness, a 'dwell' or 'spark-out' period is required to allow for recovery of the deflection after the programmed infeed position should have been reached. Conventionally, the length of the dwell period is determined using arbitrary rules. The dwell period determined in this way tends to be conservative to cope with variations in grinding force and therefore, the cycle time in conventional grinding is longer than necessary. A consequence of the extended cycle is that the wear of the grains is increased, which increases the deflections and requires an even longer dwell period.

A feature of inefficient grinding is increased likelihood of workpiece thermal damage. A large number of grains sliding and cutting on the workpiece surface can generate a large quantity of heat. The heat generated in the contact zone is mainly conducted into the workpiece and the grinding wheel so that thermal damage can easily happen if the specific energy is too high.

As the grinding wheel removes material from the surface of the workpiece, the grains experience high temperatures and stresses. It is hardly surprising that grinding wheels are themselves worn away in the process. Grinding wheel wear influences not only workpiece size but also the possibility of workpiece thermal damage. It also influences the efficiency of the grinding process. The wear is more significant when the cycle time is long. It is therefore found that the grinding conditions are subject to variation as a result of grinding wheel wear and variable system stiffness. To cope with these variations the grinding control parameters need to be varied in order to increase productivity, to prevent workpiece thermal damage and to obtain satisfactory workpiece geometry including size, roundness and roughness.

2 Strategies for adaptive control

Rowe identified the most important features required to achieve maximum production rate for a specified accuracy requirement [1] [2] [3]. The features were

- Adaptive infeedrate
- Adaptive workspeed
- Adaptive dwell time
- Adaptive target position with and without gauging
- Adaptive wheel wear compensation with and without gauging

The five features and their combinations are included in the system and incorporate the previously designed adaptive grinding cycles.

2.1 Adaptive infeedrate

Adaptive infeedrate is one of the most

popularly used strategies in plunge grinding control. The aim of controlling infeedrate adaptively is to make the infeedrate as high as possible subject to the constraints of target grinding power, maximum surface roughness and maximum workpiece temperature.

Adaptive infeedrate is illustrated in Figure 1 (a). After each infeed cycle, a new infeedrate is set based on the power measured in the previous cycle and the specified target grinding power. As infeedrate is increased, the total cycle time is reduced.

It has been proved that it is safe to adjust infeedrate on the basis that infeedrate is proportional to grinding power. When increasing infeedrate, grinding power is increased proportionally or slightly less than proportionally. Infeedrate can be increased adaptively subject to satisfactory surface roughness which is checked manually from time to time. If the surface roughness is too high, it usually means that the wrong grinding wheel is being used. However, it may be necessary to limit the target power where the correct grinding wheel cannot be used. By varying the infeedrate, the grinding power is made to match the target grinding power. The target grinding power is within the control of the operator. A lower target power may be selected where it is required to achieve very close control of size. A higher target power will be selected when high removal rate is the priority. The control law for adjusting infeedrate is

$$V_{f_{new}} = k\, V_{f_{old}}[1 + \frac{P_{target} - P}{P}] \qquad (1)$$

The factor k is a convergence coefficient which influences the rate at which the grinding power converges towards target power. A low value of k results in slow response and a high value of k results in an oscillatory response.

2.2 Adaptive target position

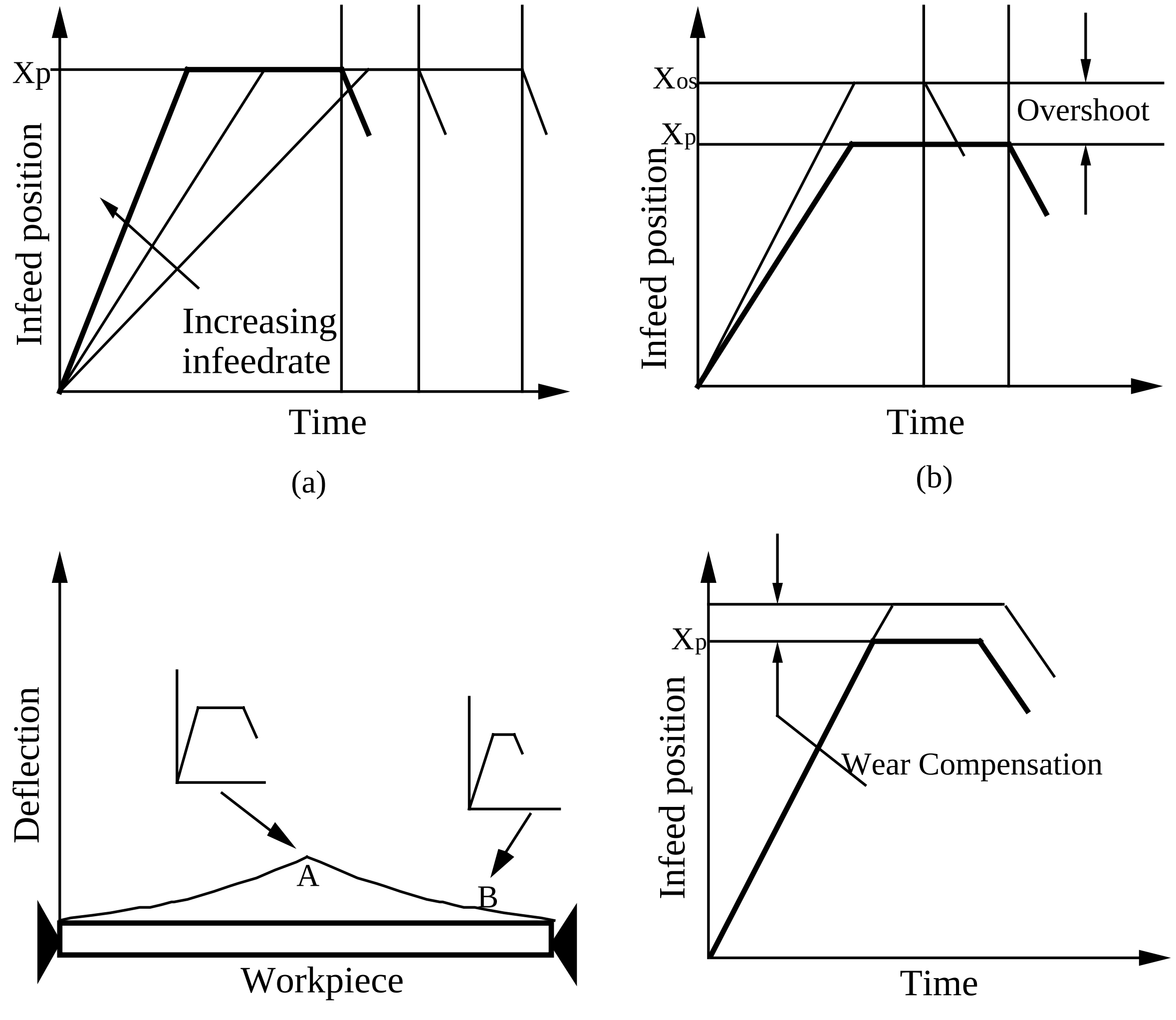
With highly compliant workpieces, the dwell period required to eliminate deflections becomes excessive. Much time is wasted and the grinding wheel is subject to increased wear. The use of adaptive overshoot can decrease total cycle time significantly. Adaptive overshoot is more effective when combined with automatic gauging.

Adaptive overshoot is illustrated in Figure 1 (b). X_p represents the conventional programmed position and X_{os} represents the overshoot position. X_p corresponds to the required size without deflection and X_{os} is the target position under intelligent control. The intelligent control system adjusts X_{os} based on the identified time constant if automatic gauging is not available. Where gauging is employed, the target position may be adjusted based on size measurements during the dwell period.

2.3 Adaptive dwell

Conventionally, the selection of dwell time for a specific grinding condition is based on the operator's experience. Such a trial and error approach often results in a conservative dwell time. Excessively long dwell reduces productivity and increases grinding wheel wear. On the other hand, a dwell that is not long enough results in a workpiece both oversize (undersize for internal grinding) and out of round. Using the strategy of adaptive dwell, the dwell time is determined based on the identified time constant and specified requirements for workpiece accuracy. The dwell time is therefore the optimum for the specific conditions. The strategy of adaptive dwell is very effective in multi-plunge grinding. With constant dwell, the different time constants at different positions along the workpiece axis cause the workpiece to be barrel shaped. Adaptive dwell avoids barrel shaped components and avoids the need for an adaptive work steady.

The concept of adaptive dwell is illustrated in Figure 1 (c). Figure 1 (c) shows the deflections along the axis of a slender workpiece in grinding. It can be seen that the deflection and time constant are greater at the mid position along the length of the workpiece. The length of the dwell should therefore be different at different positions.



(a) (b)

(c) (d)

Figure 1 Strategies for intelligent control: (a) adaptive infeedrate (b) adaptive overshoot (c) adaptive dwell time (d) adaptive wheel wear compensation

2.4 Adaptive wheel wear compensation

Wheel wear compensation when automatic gauging is employed is relatively straightforward and can be combined with a degree of overshoot. The dwell time can be measured and if it is too short, it is clear that wear compensation is required. The calculation of the compensation is based on the time constant [4] [5]. Using the adaptive wheel wear compensation strategy, the offset for wheel wear compensation can be calculated based on the compliance model and time constant measurements. The target infeed position can be controlled based on the result of the calculation.

Adaptive wheel wear compensation is illustrated in Figure 1 (d). Wheel wear is compensated by applying an offset to the programmed infeed axis position.

2.5 Adaptive workspeed

Workspeed does not strongly influence grinding power. However, it influences workpiece surface quality. When increasing workspeed, the material removal rate will not necessarily be increased in cylindrical grinding so that productivity will be unaffected. Reducing workspeed will increase the risk of thermal damage, while increasing workspeed increases the risk of chatter. In practice, it is found that in the region of an optimum, the process is insensitive to workspeed so that once set the workspeed is usually maintained constant unless problems are experienced.

When thermal damage occurs to the workpiece surface, increasing workspeed is an effective means to avoid thermal damage because the workpiece surface passes through the contact zone more quickly.

Adaptive workspeed is illustrated in Figure 2. The curves in Figure 2 represent the burn limit, chatter limit and power limit. Figure 2 shows the optimisation of the grinding process under the constraints of workpiece burn, chatter and available power. The foundation of the optimisation was established by Rowe [6]. The maximum removal rate was achieved by varying infeedrate and workspeed. It was suggested that the optimum grinding condition was within the region enclosed by the boundaries of burn, chatter and power. Thermal damage may be avoided by controlling workspeed adaptively. More importantly, a thermal damage monitor can indicate to the operator the proximity to the burn boundary and thereby give an indication of the need to redress the grinding wheel. A thermal damage monitor has been developed which calculates the actual specific energy and the critical specific energy to enable the operator to monitor the possibility of thermal damage.

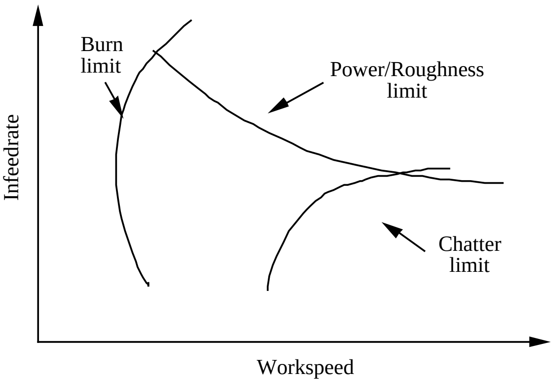


Figure 2. Adaptive workspeed

3 Identification of the time constant

3.1 Introduction

Allanson described two approaches to in-cycle time constant identification [4]. One approach employed was to identify the time constant during an infeed stage. The other approach was to identify the time constant during the dwell period. The feedback signals used to identify time constant were the power signal from a power sensor or the size signal obtained from a gauging device.

In the generic intelligent control system, the power signal was used to calculate the time constant because the power signal is widely available with very little cost. Another reason to use the power signal is that the data acquisition system can be made independent of the particular CNC which performs conventional grinding cycle control. This feature makes the GICS easy to integrate with different CNCs. The algorithms to identify time constant in the infeed stage and in the dwell stage were programmed in the generic intelligent control system. The use of the particular algorithm is decided according to the specific control requirements and the specific conditions.

3.2 Procedure

The procedure for determining the system time constant from the integral of grinding power is illustrated in Figure 3. The technique for time constant identification based on power integration was developed by Allanson [7]. The procedure consists of six main steps.

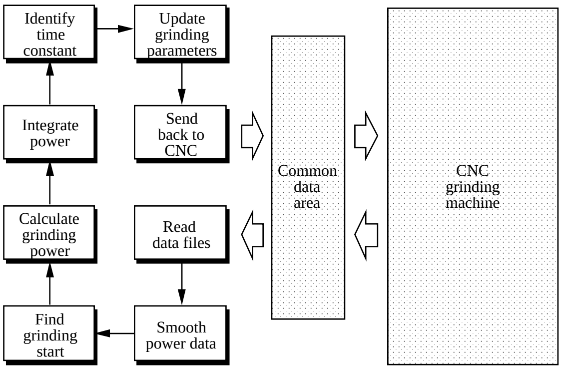


Figure 3. Time constant identification procedure

During the grinding cycle, grinding power data are acquired from the grinding machine and are stored in the file named "gpower" in the common data area shared by the generic intelligent system and a virtual CNC system. At the same time, the programmed grinding parameters such as the stock to be removed in the coarse grinding stage, the stock to be removed in the fine grinding stage, the coarse infeedrate, the fine infeedrate and the dwell time are saved in the file named "gparam" in the common data area.

Step 1: Reading the data files. The generic intelligent system reads the two data files "gpower" and "gparam" from the common data area. The data from "gparam" are stored in the array "progdata". These data are used in calculations for grinding parameter updating and thermal damage.

The data stored in the file "gpower" are read into several two-dimensional arrays "temp_store". On opening the file, the system first detects the cycle start flag which marks the beginning of a grinding cycle. The cycle start flag is necessary when the grinding mode is multi-plunge, which means one grinding operation includes several plunge cycles. By means of the cycle start flag, the data from the file are separated into several segments, each segment is contained in one of the arrays "temp_store".

In reading the power data, the system detects how many plunge cycles have been performed, the number of data points, the number of non zero data points and the maximum power in each cycle. Based on the number of data points in a cycle, the cycle time can be calculated for each cycle. The power data stored in "temp_store" and the number of non zero data are used in the next step.

Step 2: Power smoothing. The data measured from the process usually include noise. The noise can influence the accuracy of the time constant identification if appropriate precautions are not taken. A smoothed power curve is fitted through the noisy data using the principle of least mean squares. The relationship between power and time during the infeed stage is assumed to be represented by equation 2.

$$P = c_1+c_2t+c_3t^2 \qquad (2)$$

Using a 5-point series P_{-2}, P_{-1}, P_0, P_1 and P_2 from measured grinding power data, the coefficients c_1, c_2 and c_3 are determined and used to correct the mid point P_0. Based on equation 2, the theoretical values of the grinding power at 5 successive time moments can be achieved and errors can be calculated. An error is the difference between the theoretical value and the actual value of grinding power. The sum of the errors squared is given by equation 3.

$$\begin{aligned}\sum_{i=-2}^{2}(P-P_i)^2 = {} & (c_1-2c_2+4c_3-P_{-2})^2 \\ & +(c_1-c_2+c_3-P_{-1})^2 \\ & +(c_1 \qquad -P_0)^2 \\ & +(c_1+c_2+c_3-P_1)^2 \\ & +(c_1+2c_2+4c_3-P_2)^2 \qquad (3)\end{aligned}$$

Setting the partial derivatives of $\sum_{i=-2}^{2}(P - P_i) = 0$ with respect to c_1, c_2 and c_3 and solving yields results shown as equations 4, 5 and 6.

$$c_1 = (-6P_{-2}+24P_{-1}+34P_0+24P_1-6P_2)/70 \qquad (4)$$

$$c_2 = (-2P_{-2}-P_{-1}+P_1+2P_2)/10 \qquad (5)$$

$$c_3 = (2P_{-2}-P_{-1}-2P_0-P_1+2P_2)/14 \qquad (6)$$

At the mid point of the 5-point series where t = 0, it is therefore known from the equation 2 that the corrected grinding power is P = c_1. The corrected value of the mid point is calculated using its original value P_0 and the values of the surrounding four points, P_{-2}, P_{-1}, P_1 and P_2.

The same method is used for all points in the power data series except the first two points and the last two points. Those four points can be smoothed using the same method but the calculation is slightly different. Since the four points are not significant for time constant identification, they are not smoothed. The power data can be smoothed as many times as required until the power curve is sufficiently smooth.

Step 3: Detection of the grinding start point. The accuracy of the time constant identification depends on the accuracy of the start of grinding. It is therefore important to determine the grinding start point. The criterion used is

IF the variance at a point ≥ the factor times the reference value
THEN grinding has started.

The reference value is determined from the no-load power. The no-load power before the grinding wheel touches the workpiece is relatively stable until the grinding wheel interacts with the grinding fluid. The initial variance of the no-load power remains reasonably constant. The variance of the no-load power is used as a reference value.

A number of data points are used in the calculation to detect the grinding start point. The calculation is shifted forward one point at a time for a certain number of data points in the data series. The variance at each point is compared with the reference value. If the criterion is satisfied at a point, the grinding start point is determined to be at that point.

The power curves for internal grinding were found to be different from those for external grinding. The power curves for external grinding and internal grinding are illustrated in Figure 4. It can be seen from Figure 4 that the difference between the two power curves is the gradual increase in the no-load power level before the grinding start point in internal grinding. The algorithm to detect the grinding start point for internal grinding is therefore different from that for external grinding.

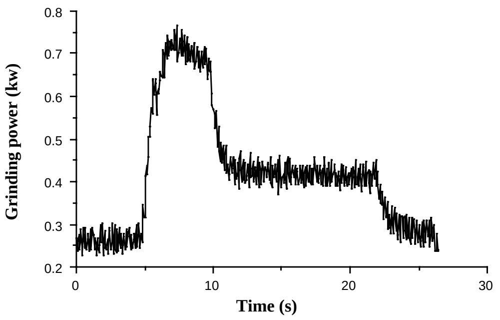


Figure 4(a). Power in external grinding

The criterion for determination of the grinding start is used twice in the algorithm for internal grinding. The criterion is first used to detect the point at which no-load power begins to increase. It is then used again to detect the grinding start point. However, the reference value is re-calculated and the value of the factor is reset for the second application of the criterion.

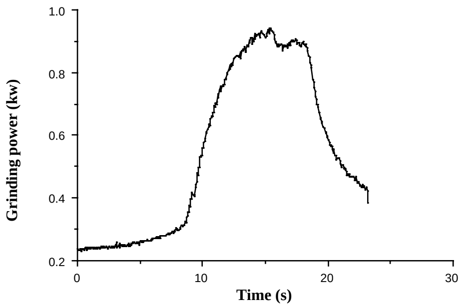


Fig 4(b). Power in internal grinding

Step 4: Grinding power. In order to identify the time constant using the power integration method, the no-load power is first subtracted from the total power at every point in the smoothed power data series.

Step 5: Power integration. The integral of power is evaluated by summing the products of power data samples and the time intervals between two samples.

$$\int_0^t P \, dt \approx \sum_{i=0}^{n} P_i \, \Delta t \qquad (7)$$

After the grinding system reaches its steady state, the integral is linear. The time constant is identified as the intercept of the integral on the time axis [5].

Initially, the curve of the power integral is non-linear. Different lines can be drawn through pairs of points on the curve and the lines meet the time axis at different points. A criterion is therefore needed to decide when sufficient accuracy has been achieved.

Step 6: Convergence criterion. The criterion adopted is based on the maximum intercept. The intercept of the power integral on the time axis is a maximum when a steady state is reached. This technique is easy to use and proved to be sufficiently reliable.

4 The overshoot calculation

The overshoot calculation is based on the compliance model developed by Allanson [4].

It has been shown for infeed control that the grinding system can be considered as a first order system. A typical input and response are illustrated in Figure 5. The input is command infeed position $x_c(t)$, the output of the system is the actual infeed position x(t). The system is represented by equation 8.

$$\tau \frac{dX(t)}{dt} + X(t) = X_c(t) \qquad (8)$$

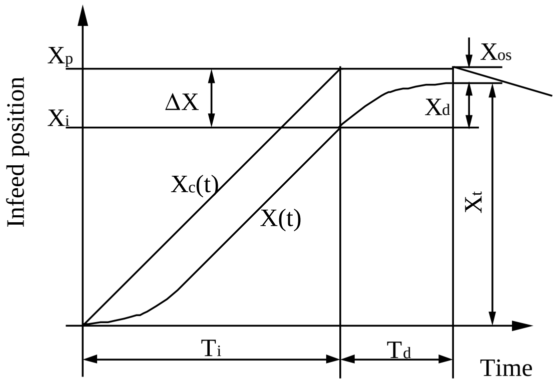


Figure 5 A typical input and response for a single infeed and dwell cycle

The overshoot calculation consists of six steps.

Step 1: Calculation of the time period, T_i required for infeed

$$T_i = \frac{X_p}{v_f} \qquad (9)$$

Step 2: Calculation of the stock removed during the infeed stage. The response, X of the system to the ramp input is represented by

$$X = v_f \, [\, t - \tau + \tau \exp(- \frac{t}{\tau})] \qquad (10)$$

At the end of the infeed stage, t = T_i, the stock removed is

$$X_i = v_f \, [T_i - \tau + \tau \exp(- \frac{T_i}{\tau})] \qquad (11)$$

Step 3: Calculation of the deflection at the end of the infeed stage. If the system deflection were zero, the stock removed at the end of the infeed stage would be X_p. The stock actually removed is X_i. The value of deflection can be obtained by subtracting the stock removed from the programmed infeed position.

$$\Delta X = X_p - X_i \qquad (12)$$

Step 4: Calculation of the stock removed during the dwell period. In the dwell stage, no infeed takes place and the system recovers elastically. The deflection can therefore be considered to act on the system as a step input. At the end of dwell, the response of the system to the step input is

$$X_d = \Delta X \, [1 - \exp(- \frac{T_d}{\tau})] \qquad (13)$$

Step 5: Calculation of the total stock removed. The total stock removed is the sum of the stock removed in the infeed stage and the stock removed in the dwell stage.

$$X_t = X_i + X_d \qquad (14)$$

Step 6: Calculation of the overshoot. The value of overshoot is the difference between the programmed stock to be removed and the stock actually removed after the infeed and dwell stages.

$$X_{os} = X_p - X_t \tag{15}$$

The overshoot infeed position is achieved by adding the value of X_{os} determined from the measured time constant to the programmed infeed position. Experience tends to show that adaptive overshoot leads to unacceptable size variations unless coupled with automatic diameter gauging.

5 Algorithm for prevention of thermal damage

The purpose of this algorithm is to compare the actual specific energy of the process with the critical specific energy which would lead to thermal damage. The algorithm for thermal damage was based on the model developed by Rowe and Black [8]. The thermal model has 16 inputs and 2 outputs, the actual specific energy e_c and the critical specific energy e_c^*. The 16 inputs are from three different sources, the user interface, the grinding machine and the object initialisation process. The inputs/outputs of the thermal model are shown in Figure 6.

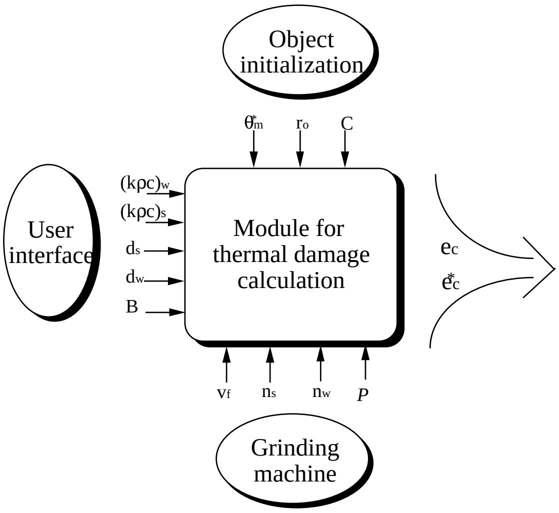


Figure 6 The thermal model and its inputs/outputs

The thermal properties and geometrical information about the workpiece and the grinding wheel are input from a window in the user interface when a new batch of workpieces are to be ground. The thermal properties include specific heat, density and thermal conductivity for both the workpiece and the grinding wheel. The geometrical information includes the diameters for both workpiece and grinding wheel and the width of cut. A total of nine input parameters are required.

The kinematic parameters and the grinding power are obtained from the grinding machine through the shared common data area. Kinematic parameters include infeedrate, workspeed and grinding wheel speed. The values are sent to the common data area as soon as the grinding cycle is started. The grinding power data are sent to the common data area during the grinding cycle.

The other three parameters, θ_m^*, r_o and C are programmed in the system through the process of object initialisation. θ_m^* is the critical temperature at which damage occurs for the workpiece material. This is set for ferrous materials to correspond to the temperature which causes significant tempering. The critical temperature can be changed for particular materials. The parameter r_o is the equivalent wear flat radius and C is the heat flux distribution factor.

The procedure for the thermal calculations is as follows.

Step 1: Measurement of the specific energy. The actual specific energy is the measured grinding power divided by the removal rate

$$e_c = \frac{P}{\pi d_w v_f b} \tag{16}$$

Step 2: Calculation of the partition ratio using the thermal model based on the material properties and the measured specific energy

$$R_w = \left[1 + \frac{0.974\,\kappa_g}{\sqrt{(\kappa\rho c)_w r_o v_s}} \frac{1}{\Phi(\zeta)}\right]^{-1} \left(1 - \frac{6}{e_c}\right) \quad (17)$$

where $\Phi(\zeta)$ is transient time function related to thermal properties of grinding wheel, grinding wheel speed, equivalent wear flat radius and contact length between grinding wheel and workpiece.

Step 3: Calculation of the critical value of specific energy which will cause burn is based on the critical damage temperature, θ_m^* for the workpiece material and the partition ratio, R_W

$$e_c^* = \frac{1}{C}\sqrt{(\kappa\rho c)_w \frac{l_e}{v_w}}\;\frac{\theta_m^*}{R_w a} \quad (18)$$

The results of the thermal calculation provide the operator with information about actual specific energy and critical specific energy. The adaptive control system automatically reduces infeedrate for the next workpiece if the threshold is exceeded unless the operator intervenes to instigate redressing or take one of the suggested remedies. A visible or available warning is given together with helpful advice.

6 Summary

Common problems experienced in grinding are discussed and appropriate control strategies are designed. Strategies are discussed for adaptive infeedrate, adaptive workspeed, adaptive overshoot, adaptive dwell time and adaptive wheel wear compensation. Algorithms are provided for time constant identification, adaptive infeedrate, adaptive overshoot and thermal damage prevention. Based on the strategies and algorithms, a variety of control routines have been developed using the object-oriented technique.

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