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Adaptive Control Optimization of Grinding

A computerized adaptive control grinding system has been developed. The system is designed to optimize both the grinding and dressing conditions for maximum removal rate subject to constraints on workpiece burn and surface finish. The control strategy of the system is based upon online convergence along a predetermined optimal trajectory derived from grinding theory. A pilot system was developed and illustrative results are presented which demonstrate its performance and the practical feasibility of the optimization concept.

Introduction

Adaptive control (AC) as applied to machine tool systems refers to control of the operating parameters in reference to measurements of the process characteristics in order to operate the machining process in a desired condition. These AC systems can be classified as either Adaptive Control Constraint (ACC) or Adaptive Control Optimization (ACO), depending on the nature of the "desired condition" [1-3]. With ACC, the "desired condition" is simply specified by fixed constraints on the control system or machining process. With ACO, the "desired condition" is to maximize an index of performance subject to constraints of the control system or machining process. In principle, an ACO system should provide better performance than an ACC system.

Although there has been considerable research on ACO systems, few, if any, of these systems are used in practice. The main difficulties encountered with such systems have been mainly in specifying an index of performance together with an appropriate control policy which is not too complex, and in developing sensors which can reliably measure the necessary process parameters in a production environment. Practically all the AC machining systems used today in production are of the simpler ACC type and seldom involve the control of more than one operating parameter. This general situation with AC machine tool systems appears to be especially true for grinding [2]. A number of ACO grinding systems have been developed [2-8], but have not been implemented industrially, at least to any significant extent. Controlled-force grinding systems [9] in use are of the ACC type.

In the present paper, a computerized ACO system is described for plunge grinding of steels. The objective of the system is to maximize removal rate subject to constraints on surface finish and workpiece burn. Both the grinding and dressing parameters are controlled based upon on-line sensing of the grinding power and off-line measurement of surface roughness. On-line convergence to the optimal conditions proceeds along a predetermined optimization trajectory derived from grinding theory. This same optimization strategy has been used for off-line grinding and dressing optimization [10]. The development of a pilot computerized ACO grinding system is described and results are presented which illustrate its operation.

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Grinding Model

The optimization strategy for the ACO system is based mainly upon the grinding model of Malkin [11-13] for plunge grinding such as illustrated in Fig. 1 for the particular case of external cylindrical grinding. The essential aspects of the grinding model which are summarized in this section include the partition of the grinding power among its fundamental components, the prediction of the critical grinding power for the burning constraint, the dependence of surface finish on process parameters, and the influence of dressing on grinding performance.

Grinding Power. The total grinding power can be considered to consist of chip formation, plowing, and sliding components:

$$P = P_{ch} + P_{pl} + P_{sl} \tag{1}$$

Each power component (Watts) can be expressed in terms of the operating parameters as follows:

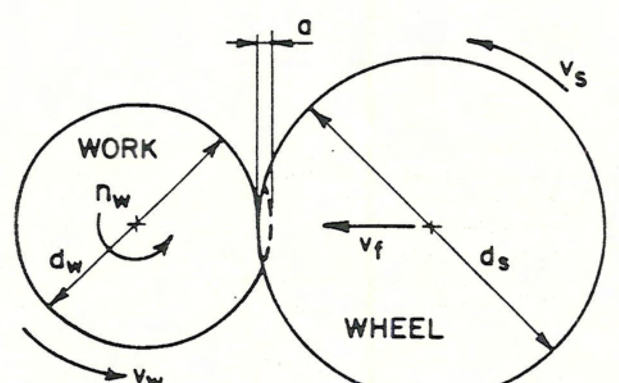

Fig. 1 Illustration of external cylindrical plunge grinding

$$P_{ch} = 13.8\,(\pi d_w v_f b) \quad (2)$$

$$P_{pl} = 0.96\, b v_s \quad (3)$$

and

$$P_{sl} = (C_1 + C_2 \pi n_w d_w / v_s d_e) d_e^{1/2} v_f^{1/2} n_w^{-1/2} b A \quad (4)$$

where d_w is the workpiece diameter (mm), b is the grinding width (mm), v_f is the radial infeed velocity (mm/s), v_s is the peripheral wheel velocity (m/s), n_w is the rotational speed of the workpiece (rev/s), and d_e is the equivalent diameter (mm) which for external cylindrical grinding is given by:

$$d_e = \frac{d_s d_w}{d_s + d_w}$$

where d_s is the wheel diameter. The expression for P_{ch} in eq. 2 is based on a constant specific chip formation energy of 13. J/mm^3 which is generally valid for grinding of both plain carbon and alloy steels of various compositions and heat treatment. The quantity within the parentheses is the volumetric removal rate. The plowing component P_{pl} in equation (3) is based on a constant tangential plowing force per unit width which is also relatively insensitive to the particular steel being ground. The sliding component in equation (4) is due to rubbing of the wear flats on the abrasive grains against the workpiece and, as such, is proportional to the fraction A of the wheel surface consisting of dulled flat area. The quantity within the parentheses in equation (4) is the frictional shear stress between the wear flats and the workpiece which includes a factor C_1 plus an additional term proportional to C_2 arising from the curvature difference between the wheel and the workpiece. For a particular case of grinding on AISI 1090 hot rolled steel, the constants are $C_1 = 7.55 \times 10^{-3}$ and $C_2 = 2.10 \times 10^{-3}$ [11]: these constants will scale up or down accordingly depending on the particular wheel-workpiece combination. With these particular values of C_1 and C_2, the wheel can be considered to have an "effective wear flat area" which may be larger or smaller than the actual wear flat area. Therefore, the expression for P_{sl} with these C_1 and C_2 values can be taken as generally valid for grinding of different steels when A is interpreted as an "effective" rather than an "actual" wear flat area.

Grinding Burn Constraint. One main limitation to the removal rate for grinding of steels is workpiece burn. On the basis of a heat transfer analysis and experimental measurements, it has been shown that burning occurs when a critical grinding zone temperature is reached [12]. The corresponding threshold grinding power (Watts) for workpiece burn can be written in terms of the grinding parameters as:

$$p_b = 19.5\, d_w v_f b + 12.8\, b d_e^{1/4} v_f^{1/4} n_w^{1/4} d_w^{1/2} \quad (5)$$

with the grinding parameters in the same units as in equations (2–4). This burning prediction has been shown to be valid for both straight surface and external cylindrical grinding is in the form of a power function relationship between the ratio of volumetrical removal rate per unit width Z/b to wheel velocity v_s:

$$R_a = R_o \left(\frac{Z}{b v_s}\right)^x \quad (6)$$

or since $Z = \pi d_w v_f b$

$$R_a = R_o \left(\frac{\pi d_w v_f}{v_s}\right)^x \quad (7)$$

with the constants R_o and x evaluated according to the surface finish for a given amount of material removal after dressing. The exponent x typically ranges from 0.4 to 0.6, although both R_o and x are reduced by extended sparkout at the end of the grinding cycle before disengaging the wheel from the workpiece.

Dressing. The manner in which the wheel is dressed can greatly influence grinding performance [15, 16]. With finer dressing (e.g., finer dressing lead or dressing depth with a single point dresser), the wheel is duller (larger A) thereby raising the grinding power in equation (2), but the surface finish is better. This tradeoff between grinding power and surface finish indicates that there should be an optimum dressing condition for a maximum removal rate subject to burning and surface finish constraints. For single point dressing, which is used in the present study, the surface finish has been found to have a power function dependence on the dressing lead f_d and dressing depth a_d [16], which when combined with equation (6) gives:

$$R_a = R_o' a_d^y f_d^z \left(\frac{Z}{b v_s}\right)^x \quad (8)$$

where R_o' is a constant. Typical values for the dressing parameter exponents are $y = 0.25$ and $z = 0.60$, which indicates that the dressing lead has a much bigger influence than the dressing depth on surface finish. A direct relationship has also been found between the effective wear flat area and these dressing parameters [17], although the need to use such a predictive equation is avoided with the present grinding optimization system.

Optimization Strategy

The performance index of the grinding process is the volumetric removal rate which for external cyclindrical grinding can be written:

$$Z = \pi d_w v_f b \quad (9)$$

The objective of the optimization is to maximize Z subject to the constraints of workpiece burn and surface finish requirements. For any particular optimization, the workpiece diameter d_w is nearly constant and the grinding width b is fixed, so the performance index can be simply taken as the radial infeed velocity v_f. The optimization problem therefore can be written:

$$\begin{aligned} &\text{Maximize } v_f \\ &\text{Subject to: } P \le P_b \\ &\qquad\qquad R_a \le R_{ax} \end{aligned} \quad (10)$$

In the present case both the wheel velocity and the wheel diameter are also considered to be constant. The variable grinding parameters are v_f and n_w, which are the parameters directly controlled on the machine tool, although a different pair of parameters (e.g., v_w and a in Fig. 1) could also be selected. Accordingly, eqs. (1–5) have been written in terms of v_f and n_w. The variable dressing parameters are f_d and a_d.

Consider first a simplified optimization problem with fixed dressing where the objective is to maximize v_f subject only to the burning constraint without any surface finish constraint. In this case, the equality condition on the power constraint applies and the optimization problem can be written:

$$\begin{aligned} &\text{Maximize } v_f \\ &\text{Subject to: } P = P_b \end{aligned} \quad (11)$$

From equations (1–5), it can be shown [18] that for a specified wear flat area A there is a particular combination of v_f and n_w which will satisfy equation (11), and this is the optimal working point (v_f^*, n_w^*) for a given equivalent diameter, wheel diameter, and wheelspeed. The collection of all the optimal points for various wear flat areas defines an optimal locus in the $v_f - n_w$ plane [17]. Several examples of optimal loci are shown in Fig. 2 for a number of equivalent diameters with v_s = 30 m/s and d_s = 440 mm, which correspond to wheel velocity and wheel diameter of the present grinding system. Any point on an optimal locus is the optimal operating point for a particular wear flat area, optimal points further out along the locus at larger removal rates corresponding to sharper wheels (smaller effective wear flat area). The complete derivation of the optimal locus relationship is presented in reference [17].

The optimal locus provides a convergence path to the optimal working point provided that the grinding power can be measured on line [17]. At the optimal working point, the equality $P = P_b$ prevails. Starting from some initial point on the optimal locus where $P < P_b$, the optimal working point can be reached by proceeding out along the optimal locus to faster infeed velocities until the measured power is equal to the corresponding burning power given by eq. (5). Likewise,

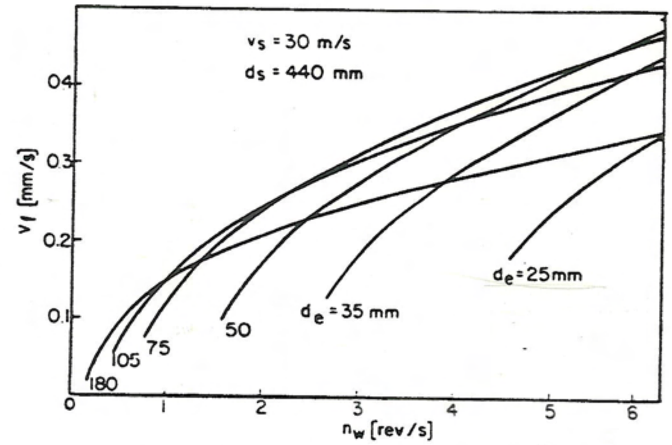

Fig. 2 Examples of optimal loci in the $v_f - n_w$ plane

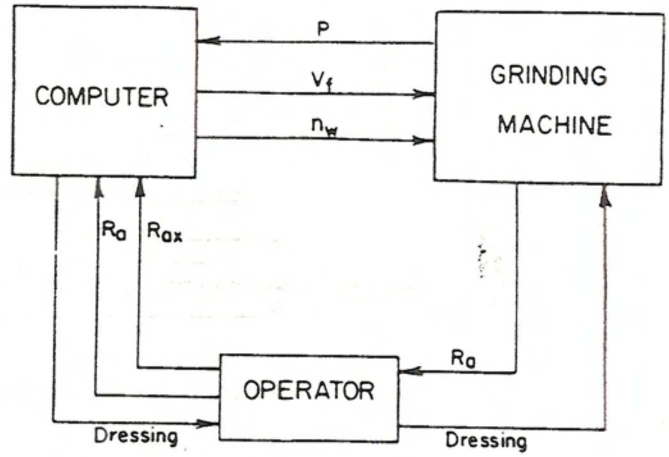

Fig. 4 Optimal adaptive control concept

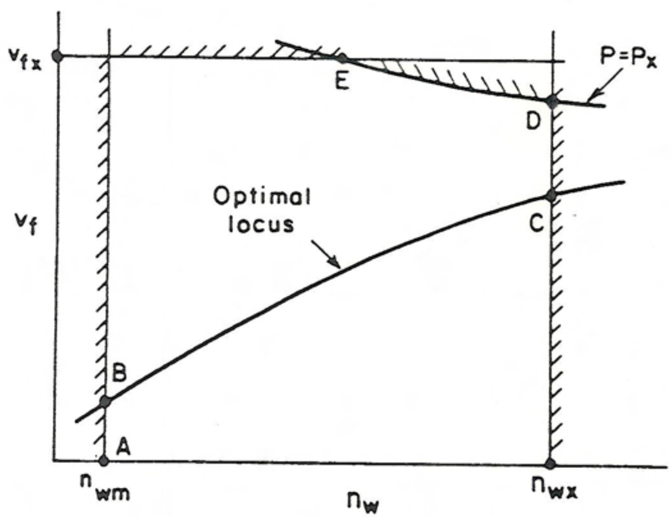

Fig. 3 Illustration of optimal locus together with machine tool limitations in $v_f - n_w$ plane

if $P > P_b$ the optimal working point can be reached by backing off along the optimal locus until $P = P_b$.

The surface finish constraint can now also be included in the optimization problem together with the burning constraint according to the optimization problem in equation (10). As the removal rate is increased by proceeding out along the optimal locus as described above, the surface finish becomes rougher (see equation (7)). The surface finish constraint may be reached prior to the burning limit ($R_a = R_{ax}$ and $P < P_b$) or vice versa ($P = P_b$ and $R_a < R_{ax}$). For fixed dressing these would be the two possible types of solution to the optimization problem in equation (10). It can be shown that further improvements in grinding performance can be obtained by altering the dressing parameters [17]. In the first case with a tight surface finish constraint, a faster removal rate can be obtained further out along the optimal locus without violating the constraints with finer wheel dressing. Likewise, if the burning constraint is tight, the dressing should be coarser. An optimal dressing condition (f_d^*, a_d^*) is obtained when both the surface finish and burning constraints are *simultaneously* active at some point on the optimal locus, which in turn corresponds to the optimal grinding point (v_f^*, n_w^*).

In addition to these surface finish and burning constraints, other constraints can arise due to machine tool limitations as illustrated schematically in Fig. 3 together with an optimal locus. These constraints include an upper limit on the infeed velocity (v_{fx}), upper and lower limits on the workpiece spindle speed (n_{wx} and n_{wm}), and maximum available grinding power (P_x). Taking these additional factors into account, the same optimization strategy described above still applies provided that a "modified" optimal locus *ABCD* in Fig. 3 is used. In principle, the section *DE* should also be included as a continuation of this modified optimal locus, since proceeding from *D* towards *E* results in increased v_f, but this additional performance is practically negligible. Another situation that can arise is that point *D* falls below point *C* on the n_{wx} constraint in Fig. 3 in which case v_f cannot exceed the point where the P_x line intersects the curve *BC*. The point *D* might also intersect the n_{wx} constraint above v_{fx} in which the P_x constraint is never reached. The point C might also lie above v_{fx}, in which case either the v_{fx} or P_x constraint would limit the performance, the prevailing constraint being the one which intersects BC at a lower radial infeed velocity.

Design of Adaptive Control System

The grinding and dressing optimization strategy described in the previous section provides a practical basis for an ACO system. The overall concept for such a system is shown in Fig. 4 which includes a grinding machine, computer, and operator interconnected. Measurements of the grinding power *P* are fed from the grinding machine to the computer, and the computer in turn controls the grinding parameters v_f and n_w to operate along the optimal locus (or modified optimal locus) and converge towards the optimal operating point. The required surface finish limit R_{ax} and periodic surface finish measurements R_a are input by the operator to the computer, and the computer in turn suggests new dressing conditions to the operator which he sets on the grinding machine. Control of the dressing could also be provided directly from the computer to the grinding machine without passing through the operator.

A pilot ACO system was developed to demonstrate this concept. This pilot system consisted of a Kellenberger 600R cylindrical grinder interfaced to a PDP-11/40 computer. This grinding machine is equipped with a 3kW main drive system giving a fixed wheelspeed v_s = 30 m/s with wheels of diameter d_s = 440 mm. The two controlled grinding parameters are workpiece spindle speed n_w and the radial infeed velocity v_f. The workpiece spindle is driven by a servo-activated DC motor in the continuous range 0.4 – 63 rev/s (n_{wm} = 0.4 rev/s and n_{wx} = 63 rev/s). For controlling the radial infeed velocity v_f, a stepping motor drive was attached to the infeed control handwheel of the machine. A Hall element sensor (F. W. Bell PX220ZB) was connected to the main drive motor to measure the machine power, the net grinding power *P* being obtained by substracting the idling power from the measured power. The net grinding power could also have been obtained by directly measuring the power force component with strain gages, but this method might not be acceptable in an industrial environment.

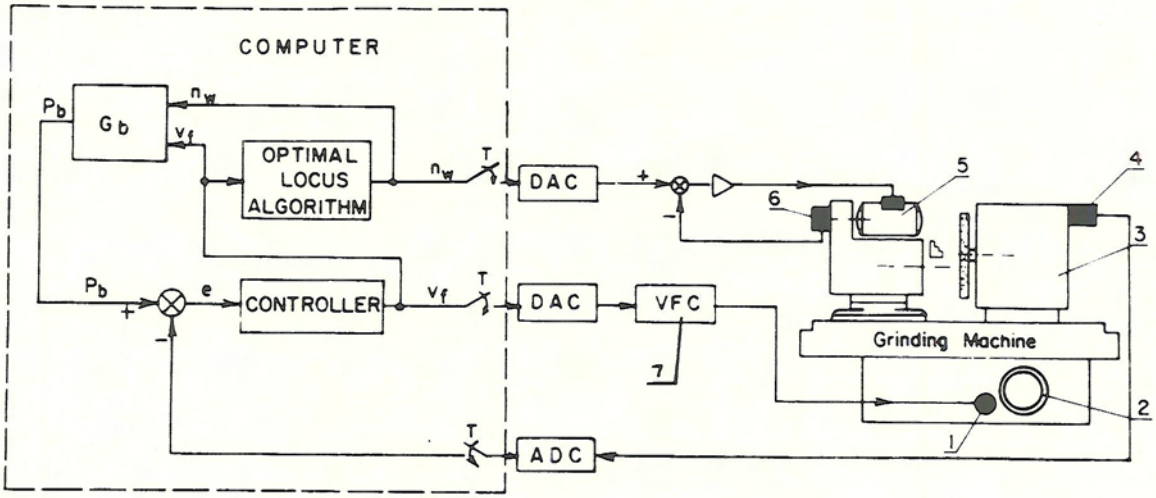

Fig. 5 On-line adaptive control system: 1-stepping motor infeed drive; 2-infeed control handwheel; 3-grinding wheel motor; 4-power sensor; 5-workpiece spindle DC motor; 6-tacho-generator; 7-voltage-to-frequency converter

A computer program was developed for controlling the grinding machine. Before grinding, the constraints ($R_{ax}, n_{wm}, n_{wx}, v_{fx}$, and P_x) and the fixed parameters (d_w, d_s, and v_s) are input by the operator to the computer. During the grinding operation, the on-line measured power is directly fed to the computer, and intermittent surface finish measurements are input by the operator. (The surface finish could also have been input on-line if a suitable transducer were available to measure the surface finish while grinding.) Based upon these inputs, the computer provides two types of outputs: on-line control signals proportional to the desired grinding parameters n_w and v_f, and a message to the operator on the computer screen suggesting new dressing parameters. Thus the system functions in a mixture of on-line and off-line modes.

The on-line control system is illustrated in Fig. 5. The heart of the control system is an algorithm incorporating the optimal locus optimization strategy described in the previous section. The grinding operation might start at an arbitrary point in the $v_f - n_w$ plane, but is immediately transferred by the computer to a point on the optimal locus by changing n_w. Thereafter, the trajectory of convergence towards the optimal operating point is along the optimal locus. For controlling the rate of convergence, instead of providing an external reference as is typically done, the reference to the control loop P_b is calculated according to equation 5 in the block G_b to which the control variables v_f and n_w are fed. As a consequence, the convergence rate depends on the error $e = P_b - P$, which converges to zero when proceeding along the locus.

From preliminary grinding experiments, the grinding power P was found to be much more sensitive to infeed velocity v_f than to the spindle speed n_w. Therefore, only v_f is directly determined by the controller in Fig. 5, and the corresponding n_w is calculated on the optimal locus. Such a single-input-single-output controller is much simpler to design than a multi-output controller. The controller algorithm was selected according to the equation:

$$v_f(i) = v_f(i-1) + K_1 e(i) + K_2[e(i) - e(i-1)] \qquad (12)$$

where the index i is the number of the sampling event. The first two terms in equation (12) constitute an integral controller of gain K_1 which ensures a zero error ($e = 0$) at the optimal point. The last term is essentially a derivative controller of gain K_2 which was added to decrease the tendency for overshooting while converging towards the optimal point. It should be noted that if the available grinding power P_x is less than the allowed power P_b, the value of P_x is used in place of P_b when calculating the error e. This situation occurred with the pilot system due to the relatively small power of the grinding machine which was available.

The adaptive control system is of the sampled-data type. Every time period T, the measured power P is sampled, the burning power P_b is calculated using the previous v_f and n_w values, and the new control parameters v_f and n_w are assigned. Between sampling events, the values of the control parameters are kept constant by storing their values in computer registers assigned to the digital-to-analog converters (DAC). As in other sampled-data systems, the selection of the sampling period T depends on the dynamic response of the process. From numerous experiments of the open-loop response of the power P to the input v_f it was found that the grinding system behavior can be approximated as a second order linear system with dead time having a transfer function:

$$\frac{P(s)}{v_f(s)} = \frac{\omega_n^2 K e^{-\theta s}}{s^2 + 2\xi\omega_n s + \omega_n^2} \qquad (13)$$

The range of numerical values of the constants for various wheels, dressing conditions, workpiece materials and diameters, and workspeeds were found to be:

damping factor	$\xi = 0.35 - 0.80$
natural frequency	$\omega_n = 0.1 - 0.2$ rad/s
dead time	$\theta = 0.1 - 0.8$ s
dc-gain	$K = 10 - 25$

It is necessary that the sampling frequency $f = 1/T$ be much greater than ω_n [12]. For the present system $f = 2$Hz was found to provide satisfactory performance. This sampling frequency was used except during rapid traverse before the wheel engages the workpiece. During rapid traverse, a much higher sampling frequency of 100Hz was used, a sudden rise in the power being taken as an indication of initial wheel-workpiece contact. After sensing initial contact, a command to slow down the infeed velocity is subsequently produced by the computer within 0.01 second, and the main control system in Fig. 5 becomes operative.

Having selected the type of controller and sampling frequency, the problem then remains to specify the controller gains K_1 and K_2. If the gains are too small, the system will respond smoothly without overshoot, but the convergence will be too sluggish. If the gains are too large, the system will have a fast response, but the damping will be insufficient. Therefore, selection of the appropriate gains represents a balance between the desirability for both fast and smooth response.

A preliminary set of experiments was carried out with the pilot system operating on the optimum locus to choose appropriate values of K_1 and K_2, and some of the results are shown in Fig. 6. In these

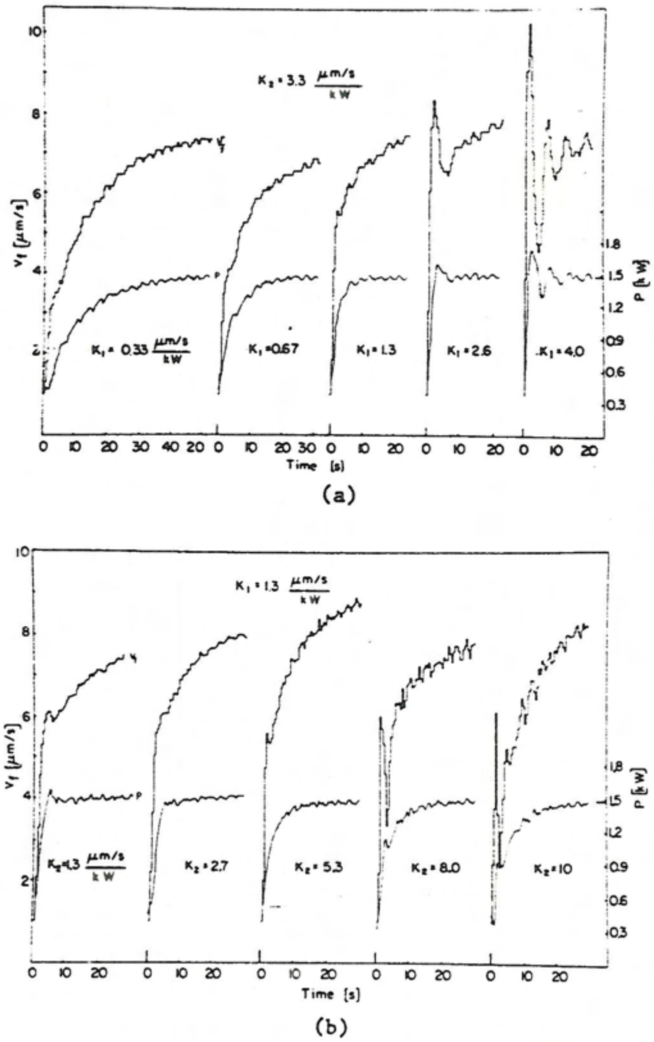

Fig. 6 Dynamic response of system for various gains K_1 and K_2: 32A46I8VBE wheel, SAE 1045 steel workpiece (190 Brinell), d_s = 440 mm, d_w = 165 mm, b = 15 mm, 0.3 mm removed from workpiece radius per cycle, single point dressing before each cycle with a_d = 10 μm and f_d = 5 μm

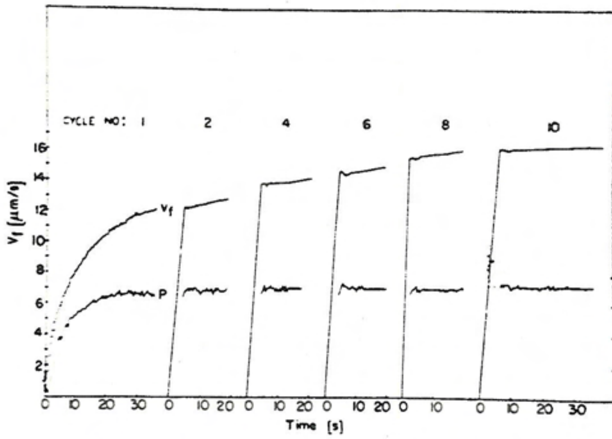

Fig. 7 Grinding of repetitive cycles with power limit constraint: 32A46K8VBE wheel, SAE 4340 steel workpiece (240 Brinell), d = 440 mm, d_w = 165 mm, b = 32 mm, 0.3 mm removed from workpiece radius per cycle, single point dressing only before Cycle No. 1 with a_d = 10 μm and f_d = 5 μm

experiments, the grinding performance was limited by the machine power limit, the net available grinding power being P_x = 1.5 kW. In Fig. 6(a), it can be seen for K_2 = 3.3 μm/s/kW that increasing K_1 gives a faster response but with undesirable overshoots at the two largest gains. Likewise for K_1 = 1.3 μm/s/kW in Fig. 6(b), it can be seen that undesirable fluctuations in v_f are obtained with the two largest values of K_2. Based on these and numerous other experiments, the controller gains of the pilot system were selected as K_1 = 3.3 μm/s/kW and K_2 5.3 μm/s/kW. These controller gains were used except when the operation approached close to the optimal operating point, as defined in the present case as the error being within 5% of the allowable power. At this point, a fast response is no longer needed to maintain optimal grinding conditions, so the gains K_1 and K_2 are substantially reduced and a software low-pass filter is added to the power line.

For repetitive grinding of identical parts, the adaptive control system makes use of a learning starting point. After the first part is ground, the system selects from the optimal grinding conditions obtained with that part a starting point for the next part. This starting point could be the same as the optimum operating point reached at the end of the previous part, or it might be preferable to choose a slightly lower infeed rate if there is significant part-to-part grinding variability. The learning starting point can be reached after rapid traverse by a constant infeed acceleration dv_f/dt, which with the pilot system was found to be limited by system stability to 3μm/s^2. The optimal control system is engaged after reaching the initial starting point.

Illustrative Results

Numerous grinding experiments were run in order to demonstrate the performance of the adaptive control grinding system, and some illustrative results are presented in this section. As mentioned above, one serious limitation with the ACO pilot system was the relatively low power of the available grinding machine, which severely limited the grinding performance. For plunge grinding with parts as narrow as b = 15 mm, the pilot system did not reach the burning limit while operating on the optimal locus. However, in a number of experiments, workpiece spindle speed values not on the optimal locus were deliberately input to the grinding system which caused burning even when operating at less than full power. This underscores the advantage of operating on the optimal locus.

Some results illustrating operation of the grinding system for repetitive grinding cycles with only the grinding power constraint are presented in Fig. 7. For Cycle No. 1, it can be seen when starting from an initial infeed velocity v_f = 1 μm/s that it takes 28 seconds for the process to converge near to the optimal point where the power line filter is activated and the gains reduced, as seen from the smoothing of the v_f curve. In the subsequent cycles, the system accelerated to the learning starting point, and the convergence time was reduced to about 4 seconds. For this series of experiments, the grinding wheel was dressed only before the first cycle. The increase in optimum infeed velocity which can be seen from one cycle to the next indicates self-sharpening of the wheel (wear flat area decreases) which is accompanied by a deterioration of surface finish. For redressing of the wheel, say after Cycle No. 10, the learning starting point for the subsequent cycle could be selected on the basis of the optimal operating condition reached in Cycle No. 1.

An example illustrating optimization of the grinding parameters v_f and n_w subject to both power and surface finish constraints is presented in Table 1. For this operation, the surface finish limit was specified as R_{ax} = 0.35 μm (CLA). The same dressing was performed before each optimization cycle using a single point diamond. At the end of the first optimization cycle, a radial infeed velocity of 4.6 μm/s was reached at the constraint $P = P_x$, but the surface finish R_a = 1.1 μm exceeded the allowable value. For the second cycle, the infeed velocity was reduced to 0.50 μ/s, which is the value predicted according to equation (7) with x = 0.5 to obtain $R_a = R_{ax}$ = 0.35μm. The resulting surface finish of R_a = 0.22μm was better than required, so the removal rate was thereafter increased to 0.71 μm/s and the resulting surface finish was 0.30μm. Considering the scatter in surface finish measurements, the optimization could have been stopped at this

Table 1 Grinding Optimization Illustration

32A46K8VBE wheel, SAE 4340 steel workpiece (240 Brinell)

d_s = 440 mm, d_w = 110 mm, b = 32 mm, 0.2 mm radial removal per cycle

Single point dressing before each cycle: a_d = 10μm, f_d = 1.0μm

Maximum allowed surface roughness R_{ax} = 0.35μm

Cycle No.	v_s (μm/s	R_a (μm)
1	4.6	1.1
2	0.50	0.22
3	0.71	0.30
4	0.86	0.55
5	0.42	0.32
6	0.46	0.42

Table 2 Grinding and Dressing Optimization Illustration

32A46K8VBE wheel, SAE 4340 steel workpiece (240 Brinell)

d_s = 440 mm, d_w = 110 mm, b = 32 mm, 0.2 mm radial removal per cycle

Single point dressing before each cycle

Maximum allowed surface roughness R_{ax} = 0.6μm

Cycle No.	v_f (μm/s)	R_a (μm)	a_d (μm)	f_d (μm)
1	5.8	1.5	10	1.2
2	4.6	0.55	10	0.40
3	4.1	0.65	10	0.34
4	4.9	0.62	10	0.37

point, but three additional optimization cycles were carried out during which the scatter in the surface finish measurements became even more apparent. These results clearly demonstrate how the surface finish requirement can impose a severe constraint on the grinding performance, in the present case leading to an order of magnitude reduction in radial infeed velocity from the initial operating point at the power limit.

For this illustrative example, a faster removal rate could have been obtained by selecting a finer dressing condition. An illustrative example including optimization of both the grinding and dressing conditions is given in Table 2, for which the surface finish limit was specified as $R_{ax} = 0.60\mu$m. For this optimization, the dressing condition was varied by changing the dressing lead f_d, and the radial dressing depth remained fixed. The initial dressing condition resulted in a rough surface finish $R_a = 1.5\mu$m at the power limit. A finer dressing condition for the next optimization cycle was selected with the aid of equation (8), and this resulted in a surface finish $R_a = 0.55$ μm at the power limit, slightly better than required, with only a rather small decrease in radial infeed velocity from 5.8 μm/s to 4.6 μm/s. These results clearly demonstrate the importance of optimizing the dressing, especially when compared with the optimization results in Table 1. Considering the typical scatter in surface finish measurements, the optimization could be considered to be complete at this point. Two additional optimization cycles were run, and the results imply that relatively small changes in the dressing are less significant than the scatter in surface finish measurements.

In these and numerous other experiments with the pilot system, regenerative grinding chatter was never found to occur, even though such chatter is generally considered to be one of the main grinding constraints [20]. The build-up in regenerative chatter is reinforced by having both a fixed wheelspeed and fixed workspeed. With the adaptive control system, the workspeed continually changes while moving along the optimal locus, thus avoiding a fixed relationship between wheelspeed and workspeed. This should suppress the tendency for regenerative chatter [21], thus providing an additional benefit from the adaptive control grinding system.

Conclusion

A computerized ACO grinding system was developed which optimizes both grinding and dressing parameters for plunge grinding of steels. The system is based upon a practical optimization strategy designed to maximize removal rate subject to constraints on workpiece burn and surface finish, although other machine tool limitations are also considered. The design and operation of a pilot ACO grinding system was described and some illustrative results were presented which demonstrate how the system converges towards the optimal conditions. This ACO concept offers the advantage of being relatively straightforward to implement, requiring the addition of a small computer, power sensor, and interface to the basic grinding machine. An existing CNC grinder can be upgraded to an ACO system using the present concept with only the addition of a power sensor and some additional software incorporating the optimal control strategy.

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