Off-Line Grinding Optimization with a Micro-Computer

Stephen Malkin and Yoram Koren, Technion-Israel Institute of Technology — Submitted by A. Ber (1)

Summary: A computer program is described for practical off-line optimization of plunge grinding operations on steels. The program is based on a strategy designed to optimize both the grinding and dressing parameters for maximum metal removal rate, subject to constraints of surface finish and burning of the workpiece. The program operates with a desktop micro-computer. When performing the optimization, the user inputs the present grinding and dressing conditions, the maximum allowable surface finish, and the measured grinding power and surface finish. The response on the computer screen displays the estimated optimal grinding and dressing parameters, suggested new trial conditions, and present grinding efficiency.

Introduction

Optimization of machining processes is usually based on finding operating conditions which minimize machining costs or maximize production rate. For performing such optimization analyses, a reliable relationship between tool life and machining parameters (e.g., Taylor equation) is generally required. Such optimization analyses can also be applied to precision grinding processes [1, 2,3] provided that suitable tool life relationships are available. For precision grinding operations on steels, the tool life (volume removed per wheel dressing) is often limited by burning of the workpiece [4], although chatter or degradation in form or finish of the workpiece may also be the prevailing constraint.

Unfortunately, it is very difficult to obtain reliable tool life equations for grinding. One form of empirical tool life equation proposed by Snoeys et al [3,5] for plunge grinding assumes a power function relationship between the volume removed per wheel dressing and the equivalent chip thickness (removal rate per unit width divided by wheelspeed). A major drawback with this relationship is the need to separately evaluate the constants in the tool life equation for each wheel-workpiece combination, dressing procedure, wheel and workpiece diameter, and even wheelspeed. Other tool life relationships have been developed by Yoshikawa [6] and Malkin [1] based upon wear models of the grinding wheel up to burning, but these are too complex for practical use.

When using a grinding optimization procedure based on tool life, it is implied that the grinding wheel degrades from an initial condition after dressing to a final condition at the end of the tool life. An optimum grinding condition exists due to the tradeoff with faster removal rates between shorter actual grinding times and the need for more frequent dressing. In many practical cases, however, the wheel is frequently dressed with relatively little unproductive time or expense, so that the wheel condition is maintained more or less constant. For this situation, which is typical of what is found in high production short-cycle grinding, the objective should be to find the "instantaneous" optimal grinding conditions. One optimization approach along this line, proposed by Mayne and Malkin [7] for plunge grinding of steels, is to maximize the metal removal rate subject to constraints on workpiece burn and finish. By applying non-linear optimization techniques to a generalized grinding model, it was analytically demonstrated how the wheel dullness, as indicated by wear flat area, influences the allowable removal rate. Selection of optimal grinding conditions using this analysis is not practical because of the need for having a reliable estimate of wear flat area.

More recently, Malkin and Koren [8] have developed a practical strategy for finding both the optimum grinding and dressing conditions for maximizing the metal removal rate subject to constraints on burning and surface finish. The strategy is based upon the same grinding model as in the previous work [7] together with additional relationships to also take into account the dressing. Use of the optimization procedure requires periodic measurement of grinding power and surface finish. This same optimization strategy is the basis for an on-line adaptive control grinding system which has been recently developed [9]. In the present paper, it is shown how this same optimization strategy is applied to off-line optimization of grinding and dressing with the aid of an inexpensive microcomputer.

Grinding Model

The optimization strategy is based mainly on the grinding model of Malkin [10] for plunge grinding, such as illustrated schematically in Fig. 1 for the particular case of external cylindrical grinding. The essential aspects of the model which are summarized in this section concern the partition of the total grinding power among its fundamental components, the prediction of the critical grinding power for workpiece burn, the dependence of surface finish on process parameters, and the effect of dressing on surface finish and wheel dullness.

(a) Grinding Power

The total grinding power per unit width can be considered to consist of chip formation, plowing, and sliding components:

$$P' = P'_{ch} + P'_{pl} + P'_{sl} \qquad (1)$$

which can be expressed in terms of the operating parameters as follows:

$$P'_{ch} = 13.8\, v_w a \qquad [\text{kW/mm}] \qquad (2)$$

with the units of workspeed v_w (m/s) and wheel depth of cut a(mm):

$$P'_{pl} = 1.0 \times 10^{-3} v_s \qquad [\text{kW/mm}] \qquad (3)$$

with the units of wheelspeed v_s (m/s):

$$P'_{sl} = (C_1 + C_2\, v_w/v_s d_e) d_e^{1/2} a^{1/2} A \qquad [\text{kW/mm}] \qquad (4)$$

where v_s, v_w, and a are as above, C_1 and C_2 are constants, A is the fraction of the wheel surface consisting of wear flat area, and d_e is the equivalent diameter (mm) given by:

$$d_e = \frac{d_s d_w}{d_w \pm d_s} \qquad (5)$$

where the plus and minus signs indicate external or internal grinding, respectively.

The above expression for P'_{ch} in Eq. (2) is based on a constant specific chip formation energy of 13.8 J/mm^3 (2.0 x 10^6 in•lb/in^3) which is generally valid for grinding steels of various compositions and heat treatments. The plowing component P'_{pl} is based on a constant tangential plowing force component per unit width of 1.0 N/mm, which is also relatively insensitive to the particular steel being ground. The sliding component P'_{sl} is due to rubbing between the wear flats and the workpiece and, as such, is proportional to the wear flat area A. The quantity within the parentheses is the frictional shear stress between the wear flats and the workpiece which includes a constant C_1 plus an additional term proportional to the curvature difference between the wheel and the workpiece. For a particular case of grinding an AISI 1095 hot rolled steel [8], the constants for Eq. (4) are C_1 = 7.55 10^{-3} and C_2 = 2.10 x 10^3. 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 in Eq. (4), the wheel can be considered to have an "effective flat area" for a given wheel-workpiece combination which may be proportionally larger or smaller than the actual wear flat area. Therefore, the expression for P'_{sl} with these values for C_1 and C_2 can be considered as generally valid for grinding of different steels when A is interpreted as the "effective" rather than the "actual" wear flat area.

(b) Grinding Burn Limit

One limitation on 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. The corresponding critical grinding power can be written [4]:

$$P'_b = 6.2\, v_w a + 228\, d_e^{1/4} a^{1/4} v_w^{1/2} \qquad [\text{kW/mm}] \qquad (6)$$

(c) Surface Finish

Another factor which limits the removal rate is the surface finish requirement. One empirical surface finish relationship proposed by Snoeys et al [3,5], which appears to apply reasonably well for cylindrical grinding, assumes a power function relationship between the surface finish R_a and the ratio of removal rate per unit width Z' to wheel velocity v_s:

$$R_a = R_o \left(\frac{Z'}{v_s}\right)^x = R_o \left(\frac{v_w a}{v_s}\right)^x \qquad (7)$$

where R_o and x are experimentally determined constants. For grinding without sparkout, x typically ranges from 0.4 to 0.6; both R_o and x are reduced by longer sparkout at the end of grinding before disengaging the wheel from the workpiece.

(d) Dressing

Optimization procedures applied to grinding processes generally do not take dressing into account, although dressing can greatly influence grinding performance. For example, Malkin and Murray [11,12] have found variations by as much as a factor of 6 in both grinding power and surface finish by only varying the dressing parameters. With finer dressing conditions (e.g., finer dressing lead or dressing depth with a single point dresser), the wheel is duller (larger flat wear area A) thereby raising the grinding power in Eq. (1), but the surface finish is better. This tradeoff between grinding power and surface finish indicates that there is an optimum dressing condition for maximum removal rate subject to burning and surface finish constraints.

It has been shown that for given grinding conditions, the tradeoff between grinding power and surface finish obtained when varying the dressing conditions is very nearly the same for both rotary and single point dressing [12]. For rotary diamond dressing the severity of dressing can be expressed in terms of a single parameter δ, which is the interference angle at which the diamonds on the rotary dresser surface engage the abrasive grains on the wheel surface. The parameter δ can be readily expressed in terms of the rotary dresser infeed velocity and peripheral velocity, and an equivalent combination of dressing lead and depth can also be specified to give the same grinding performance with single point dressing. Therefore, the severity of the dressing process for both single point and rotary dressing can be described in terms of a single parameter δ.

For the purpose of present optimization, it is necessary to show the effect of dressing on wear flat area and surface finish. For the limited data available, the relationship between effective wear flat area and δ can be shown to follow an inverse semilogarithmic relationship [8]. For both rotary and single point dressing, it has been shown that the surface finish is proportional to $\delta^{1/3}$ [11, 12], and other surface finish measurements can be shown to follow the same dependence on dressing [8].

Taking this into account, the surface finish relationship of Eq. (7) can be rewritten:

$$R_a = R'_o \, \delta^{1/3} \left(\frac{Z'}{v_s}\right)^x \qquad (8)$$

where R'_o is a constant for a given wheel-workpiece combination and equivalent diameter.

Optimization Strategy

The performance index for the grinding process is the volumetric removal rate per unit width:

$$Z' = v_w a \qquad (9)$$

The optimization objective is to maximize Z' subject to constraints of workpiece burn and surface finish. This optimization problem can be written:

$$\begin{aligned} &\text{maximize } Z' \\ &\text{subject to } P \leq P_b \\ &\qquad\qquad R_a \leq R_{ax} \end{aligned} \qquad (10)$$

where R_{ax} is the maximum allowable surface roughness. A practical optimization strategy to achieve this objective has been developed [8] and the main ideas are briefly reviewed in this section.

Consider first a simpler optimization problem where the burning constraint is included but the surface finish constraint is not. With this single constraint, the equality condition on the power constraint applies so that $P = P_b$ in Eq. (10). From Eqs. (1-6) it is apparent that for a specific given wear flat area A, there is only one combination of v_w and a which will maximize the product $v_w a$ with $P = P_b$, and this corresponds to the optimal working point (v_w^*, a^*). For a given equivalent diameter and wheelspeed, the collection of all the optimal points defines an optimal locus in the v_w - a plane. Such an optimal locus and its general shape is schematically illustrated in Fig. 2. Any point on the locus is the optimal operating point for a particular wear flat area, the optimum points further out along the locus at larger removal rates corresponding to sharper wheels (smaller wear flat area).

In order to arrive at the maximum removal rate without burning, it is now necessary to find the optimal point (v_w^*, a^*) lying on the optimal locus at the appropriate effective wear flat area. This optimal point corresponds to the burning limit where $P = P_b$, and can be readily found provided that the grinding power can be measured. One procedure to achieve this would be to proceed out along the locus from some initial point where $P < P_b$ towards faster removal rates while monitoring the machine power. The optimal point is reached when the measured power P equals the corresponding burning power P_b.

The procedure described above neglects the surface finish as a possible constraint. As the metal removal rate is increased by proceeding out along an optimal locus to faster removal rates, the surface finish becomes rougher according to Eq. (7). If the surface finish constraint is now also introduced into the optimization problem, it is apparent that the surface finish limit 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 conditions, these would be the corresponding solutions to the optimization problem defined in Eq. (10). For the first case where the surface finish constraint is tight, it can be shown that a faster removal rate can be obtained within the specified constraints with finer dressing. Likewise for the second case where the burning constraint is tight, a faster removal rate can be obtained with coarser dressing. The optimal dressing condition is obtained only when both the surface finish and burning constraints are simultaneously active at some point on the optimal locus, which in turn corresponds to the optimum grinding condition (v_w^*, a^*).

Optimization Program

The optimization analysis provides the basis to arrive at optimal grinding and dressing conditions for plunge grinding of steels with the aid of the appropriate optimal locus relationship together with periodic grinding power and surface finish measurements. Within this framework, the optimization objective is to find those grinding and dressing conditions such that both constraints become simultaneously active on the optimal locus.

In order to facilitate the optimization procedure in practice, an interactive computer program was developed to run on an inexpensive desktop microcomputer (8K memory). The flow chart for the computer program is shown in Fig. 3. The user first chooses the type of grinding, the grinding parameters to be optimized (v_w and a, or v_w and v_f), the system of units (SI or English), and whether the dressing method is single point or rotary. The fixed parameters are then entered including d_s, d_w, v_s, R_{ax}, the the grinding width b, and a safety factor B which is the ratio of maximum allowed grinding power to the predicted burning power.

The conditions specified up to this point remain fixed. Grinding is then carried out for which the variable grinding and dressing parameters are entered to the computer together with the measured grinding power P and surface finish R_a. The measured power as a percentage of the allowed burning power is calculated and displayed, taking into account the factor B.

The optimization procedure is now carried out twice, the first time (counter CN = 1) to obtain suggested trial conditions, and the second time (CN = 2) to find the optimal conditions. As a basis for selecting trial conditions, the measured grinding power is first multiplied by a factor of T (T>1) before entering the optimization routine. The factor T is chosen according to a policy whereby the suggested trial conditions fall on the optimal locus between the present and optimal conditions. With CN=2, the factor T is eliminated, and the estimated optimal conditions are calculated. At the end of both optimizations, the computer displays the suggested new trial conditions, optimum grinding and dressing conditions, and the process efficiency which is the ratio of the present removal rate to the computed optimal removal rate. The grinding process can now be carried out again with improved grinding conditions, which can be selected on the basis of the suggested trial conditions. These grinding and dressing parameters are input to the computer together with measured power and surface finish as before, and suggested new trial and optimal conditions are obtained from the computer. By repeating this optimization procedure with continued grinding, the trial conditions tend to converge toward the optimal.

Aside from using the computer program in this interactive mode, it can also be applied to the evaluation of existing grinding operations. The grinding and dressing data for the grinding process are input as above, and the prospects for improving productivity can be readily identified from the computed process efficiency. Up to now the program has been industrially used mainly in this latter mode, as it allows for evaluation of grinding processes without disturbing production.

To illustrate the use of the program, the following grinding operation was evaluated:

External Cylindrical Grinding
Optimize parameters v_w and a
SI Units
Single Point Dressing

Fixed Parameters:

wheel diameter	d_s = 450 mm
work diameter	d_w = 80 mm

wheelspeed $v_s = 30$ m/s
grinding width $b = 20$ mm
maximum finish $R_{a\,max} = 0.6$ μm
power safety factor $\beta = 100\%$

Variable Parameters:
radial dressing depth $a_d = 0.01$ mm
dressing lead $f_d = 0.05$ mm
workspeed $v_w = 30$ m/min
wheel depth of cut $a = 0.01$ mm
grinding power $P = 3.1$ kW
surface finish $R_a = 0.4$ μm

Computer Output:
percent allowed power = 87%

dressing too fine: increase f_d to 0.055 mm or increase a_d to 0.013 mm

optimal workspeed, $v_w^* = 67$ m/min
optimal depth of cut, $a^* = 0.009$ mm

trial workspeed, $v_{wt} = 51$ m/min
trial depth of cut, $a_t = 0.01$ mm

process efficiency = 50%

In this example, the grinding power is less than the allowable limit and the surface finish is better than required. By altering the grinding and dressing parameters, it should be possible to approximately double the removal rate. The suggested trial conditions correspond to a 70% increase in removal rate. When incrementing the removal rate by such large amounts, excessive wheel breakdown sometimes occurs beyond a certain point. In such a case, a harder grade of wheel should be used. By carrying out the optimization on a series of wheels of various grades, or with wheels from different manufacturers, wheel selection can also be optimized.

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Nomenclature

a - wheel depth-of-cut
a_d - radial dressing depth
A - wear flat area
b - grinding width
B - burning power limit factor
C_1, C_2 - constants
CN - counter number
d_e - equivalent diameter
d_s - wheel diameter
d_w - work diameter
f_d - dressing lead
P - grinding power
P' - grinding power per unit width
R_a - surface finish

R_o, R'_o - constants
T - power factor for trial
v_f - radial infeed velocity
v_{rf} - rotary dresser infeed velocity
v_s - wheel velocity
v_{rs} - rotary dresser peripheral velocity
v_w - workpiece velocity
Z - volumetric removal rate
Z' - removal rate per unit width
δ - interference angle for rotary dressing

Subscripts
b - at burning limit
ch - chip formation
pl - plowing
sl - sliding
m - minimum
t - trial condition
x - maximum

Superscripts
$*$ - optimal condition

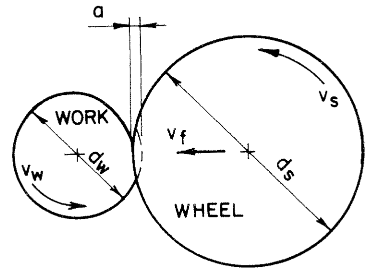

Figure 1. Illustration of external plunge grinding.

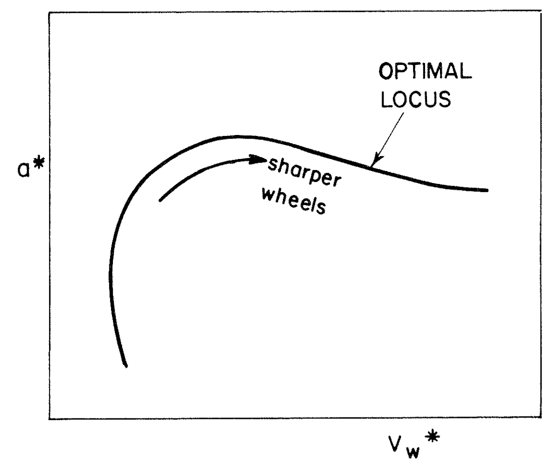

Figure 2. Illustration of optimal locus.

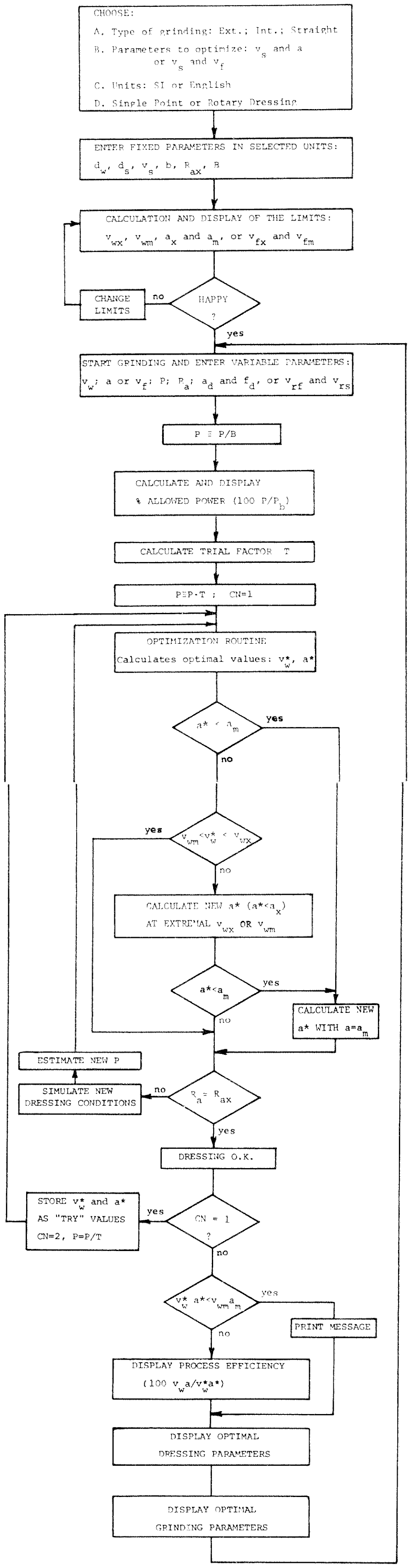

Figure 3. Flow chart for optimization program.