Adaptive Control Optimization of Grinding

Milton C. Shaw. The authors have identified an important approach to adaptive control in which the operator acts as the interface between machine and computer. This idea, which is particularly attractive in a period of shortage of investment capital and soaring interest rates, has been given a name, manual adaptive control (MAC), to distinguish it from the ultimate in manufacturing sophistication and amount of capital required, automatic adaptive control (AAC). When MAC was introduced several years ago, it was suggested that the operator also act as the set of sensors and that an inexpensive (~$200) programmable hand-held calculator serve as the computer to further decrease the capital investment involved.

The MAC system merely transfers the computational and decision-making skills from engineer to operator via the programmed computer. The optimization process begins at a set of operating conditions suggested by a "data bank" or machinability handbook that gives the best available estimate of operating conditions for the given operation, machine and tool and work, material combination. However, a data bank cannot cover all possible variations and will generally predict the best average set of operating conditions. The job of MAC is to fine-tune the data bank entry by changing the rate of removal in small steps and entering the result, usually in terms of parts produced per tool change and total time elapsed. The programmed computer determines the value of the optimization variable, compares it with the previous value taken from storage, and tells the operator to continue in the same direction or to reverse the direction of the incremental change. Tool life (T) (volume of material ground between dressing operations in the case of a grinding operation) is found to vary experimentally with removal rate (Z) in accordance with the following Taylor-like equation:

\[ TZ^4 = B \]

where A and B are constants, and A is related to the reciprocal of the well-known Taylor exponent. It is because of this basic relationship that an optimum removal rate exists for all removal operations, including grinding.

In considering optimization of a removal operation, it is important to choose the proper optimization variable at the outset. Optimization variables may be classified as being primary or secondary in terms of whether they directly represent the desired goal or are one or more steps removed. In practically all cases, there are but two primary optimization objectives—either production at minimum cost per part or at maximum production rate. In times of capital shortage, as at present, or in case of a national emergency or production bottleneck, maximum rate of production is apt to be the more important optimization objective. The adaptive control system described by the authors is an example of optimization involving a secondary variable—removal rate. The maximum removal rate will, in general, correspond to neither minimum cost nor maximum production rate. Only by including the cost and time of dressing in the optimization procedure can optimization of either of the primary variables be achieved. If the maximum removal rate possible requires frequent dressing and dressing time and cost is significant, as it usually is, then something less than maximum removal rate will represent the true optimum.

The authors have highlighted two important constraints on increased rate of removal in grinding—surface finish and burn. In general, there are many more constraints. By having the operator act as the large combination of sensors required in automatic adaptive control, the MAC system provides a further important decrease in capital required for employing adaptive control.

The MAC system has been successfully applied to a number of material removal operations, including several grinding operations [4–6]. In one centerless grinding application, the cost per part was reduced by a factor of two compared with operations [4–6]. In one centerless grinding application, the cost per part was reduced by a factor of two compared with operations [4–6].

References

Authors' Closure

The comment made by Milton C. Shaw claimed mainly that:

1. The optimization parameter that was chosen (i.e., removal rate) in the optimization strategy is a secondary parameter, while a primary parameter (i.e., cost or production rate) would be preferable.

2. There are many more constraints to be taken into account than those that were chosen (i.e., burn and surface finish).

Referring to the first claim, it is true that theoretically the cost or production rate must be extremized as classically suggested in all metal cutting processes, but it is also well known that in order to establish cost or production functions, one must rely on estimated time and cost constants and on an experimental tool life equation. In all metal cutting processes, including grinding, there is a lot of scatter in the empiric tool life equation, and a lack of confidence in the estimated constants.

Instead of aiming at the theoretical optimum, which we believe cannot be practically achieved, we have chosen the metal removal rate, which can be measured on-line, as the optimization parameter. Introducing on-line automatic dressing, which we have suggested, will force the maximum metal removal rate that is achieved to cause maximum production rate (knowing that the wear of the grinding wheel due to the dressing is automatically compensated). In fact, as grinding wheels are cheap relative to the whole grinding process, it seems that the optimization for maximum production rate will practically lead to the minimum cost too.

The main point that we would like to emphasize is that the most important optimization parameter was found to be the dressing. In our system, we controlled, on-line, the speed and feed of the workpiece in order to achieve maximum metal removal rate, and off-line, we optimized the dressing parameters, the influence of which was found to be significantly important in relation to the other parameters. Thus, it seems that the dressing is the primary optimization parameter because it is practically impossible to add the dressing parameters into the classic economic functions.

Referring to the second claim, there are many other constraints that can be taken into account, but none of them has (as far as we know) a reliable function describing its dependence on grinding parameters. On the other hand, surface burn (which is of great significance) gave us a reliable function that could be used in our optimization algorithms.

We find that the burn constraint dictating the metal removal rate and the surface finish constraint controlling the dressing optimization are the two most important "general purpose" constraints. For any special purpose grinding operation, other constraints must be involved and it seems very practical to use the MAC method, mentioned by M. C. Shaw, which should be less sensitive to inaccuracy in the mathematical models.