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by

E. Rose and P. P. Kanjilal

Department of Control Engineering
University of Sheffield
Mappin Street, Sheffield S1 3JD

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E. Rose and P. P. Kanjilal

Department of Control Engineering, University of Sheffield, Mappin Street, Sheffield S1 3JD, England

Abstract. The paper is concerned with the design of a feedforward control scheme aimed at minimising the waste product from a sinter strand process by manipulating strand speed. The results of simulation exercises are discussed in which the sinter bed is assumed to be composed of a series of lumped sections. The velocity of the flame-front within a section is assumed to be nonlinear and initially proportional to the raw-mix permeability. Permeability data from plant are used as input and strand speed and acceleration are constrained to lie within practically realisable limits. The results of simulation exercises using simple control laws based on straight and weighted averaging of ideal section speeds are presented. The proposed new control law involves a technique for modifying the time-shift increments associated with the straight-average law. The reduction obtained in output waste from the strand when the new control law is used is clearly demonstrated.

Keywords. Feedforward control; simulation; steel industry; sinter strand.

INTRODUCTION

A sinter strand process consists of a travelling grate onto which raw material is loaded in the form of micropellets composed essentially of iron ore fines, coke, water and rejected sinter returned for re-processing. The material is levelled to form a flat bed. The surface of the bed is ignited and, under the influence of a suction fan situated below the bed, a heat-wave is drawn downwards through the bed. The heat-wave first reaches the bottom of the bed at a point along the strand known as the burnthrough position, which ideally should remain fixed near the output end of the strand. The process is required to produce sinter of prescribed uniform strength and quality (Fleming, Hofmann, Schmit, 1977). This is partly achieved by carefully controlling the composition of the raw-mix loaded onto the strand and partly by manipulating strand speed.

The paper is concerned with the design of a feedforward control scheme aimed at minimising waste product. A new control law is developed and the results of simulation exercises are discussed in relation to those obtained when simpler control laws are used. Compared with previous studies (Dash, Rose, 1978; Rose, 1980) greater attention is given to ensuring that strand speed and acceleration are within practically realisable limits. Also the nonlinear nature of the flame front velocity is taken into account.

SIMULATION OF THE PROCESS

The sinter bed is represented by a large number n of lumped sections, Fig. 1, and horizontal motion is simulated by shifting all sections one place after a time interval Δt, where $\Delta t = \ell/nv$. ℓ is the length of the bed; v is the strand speed, which is assumed constant during the time interval and is updated after each interval.

The processing of material within each section as it is drawn along the strand is similar to that of a static section (as used in a test-pot) provided that the ignition and suction conditions are identical to those applied to a moving bed. The flow of gas is assumed to be vertical and interaction between sections is neglected. During processing, the effective permeability of the material within a given section varies according to the curve shown in Fig. 2 which for convenience is approximated by four straight-line segments. A change in the initial permeability of the incoming material is dealt with by effectively shifting the curve vertically, so that its shape is not changed but it has a correct value at $t = 0$, (Ball and colleagues, 1973). The flame-front velocity within a section at any given time is assumed to be proportional to the effective permeability of the material in the section at that time.

CONTROL PHILOSOPHY AND PRACTICAL CONSTRAINTS

A feedforward control scheme is proposed in which the permeability of the raw-mix is measured before ignition, Fig. 3. By continually recording and storing this information together with strand speed the exact state of all sections of the bed at any time can be calculated. In particular, estimates for the flame front positions and velocities are required. Since the permeability from one section to the next may vary, each section ideally needs to be driven at a different speed. The control laws considered here provide a compromise speed aimed at minimising the amount of waste produced from the strand.

Definition of Waste

In the case of a section which "underburns", the flame front does not reach the bottom of the bed by the time the section is in its final position on the strand. The volume of material below the flame front divided by the time interval for which the section occupies the final position is taken as the incremental wastage rate of undersintered material. When the flame-front reaches the bottom of the bed before the section is in its final position, the simulation allows the flame-front to notionally progress below the bottom of the bed and the incremental wastage rate of oversintered material is then calculated by dividing the volume below the bed when the section is in its final position by the time interval for which the section occupies that position. The total accumulated waste which is taken as a measure of performance is obtained by adding the integrated undersintered and oversintered volumes with a 2:1 weighting factor, on the principle that, in practice, undersintered material forms the greater proportion of the rejected sinter.

Availability of Plant Data

For the present studies plant data for raw-mix permeability were available at two-minute intervals only. It has therefore been assumed that during each two-minute interval raw-mix permeability remains constant.

Speed and Acceleration Limits

It is assumed that the strand speed may be allowed to vary about its normal value by 50%. An empirical approach is used to limit the rate at which the speed may change. No firm information was available for strand inertia and driving torque, nor is it known how suddenly it is desirable to allow speed to change taking into account the effect which a disturbance may cause to the material on the strand. For each increment the speed allowed is taken as the average of the calculated speed for that increment and the actual speeds for the three previous increments, thereby smoothing the speed changes.

THE CONTROL LAWS

Control Law 1: Straight Average

The first control law to be tried was proposed by Dash and Rose (1978). The calculated speed is obtained by averaging the ideal speeds for each of the sections forming part or whole of the bed, i.e.

$$v_a = \frac{1}{n-r} \sum_{i=r+1}^{n} v_i \ .$$

Control Law 2: Weighted Average

A modified control law involving the use of a weighted average was proposed by Rose (1980). This law is designed to give progressively greater weighting to sections as they approach the output end of the strand

$$v_{wa} = \frac{2}{(n-1)(n+r+1)} \sum_{i=r+1}^{n} i v_i$$

Control Law 3: New Control Procedure

The new control procedure is essentially a development of Control Law 1. [The same kind of refinement can be applied to Control Law 2, with similar results (Kanjilal, 1980)].

Let t_{b_i} be the time to burnthrough for the i'th section.

Using the averaging method, v_a is the calculated speed with which the i'th section (and all other sections) should be driven.

Before the material in the i'th position shifts into the (i+1)'th position, the predicted onstrand time remaining for that section of material is $(n-i)\Delta t$ where $\Delta t = \ell/nv_a$.

Let the predicted time error for the i'th section be t_{e_i}; then $t_{e_i} = t_{b_i} - (n-i)\Delta t$.

Now the magnitude of t_{e_i} indicates the predicted amount of waste for the i'th section. If t_{e_i} is positive, the material will underburn and if negative it will overburn. Therefore in subsequent calculations, consistent with the views expressed earlier on positive and negative waste, a positive/negative time-error weighting factor of 2 is applied.

An average time error t_{ea} may be calculated for all sections considered in the control law by using the formula

$$t_{ea} = \frac{1}{n-r} \sum_{i=r+1}^{n} t_{e_i} \ .$$

The new control law defines a shift time which is weighted to take into account the average time error, i.e. shift time = $\Delta t - kt_{ea}$, where k is a constant. The corresponding strand speed is therefore

$$\frac{\ell}{n(\Delta t - kt_{ea})}$$

subject to the application of the speed and acceleration constraints discussed earlier.

RESULTS OF SIMULATION INVESTIGATIONS

Procedure and Presentation of Results

Each trial is conducted for a period corresponding to approximately eight complete strand passes and in the controlled cases an iteration is carried out each time the bed is shifted by approximately 1/100 of a strand pass. Initially, the bed is assumed to be composed entirely of material having the same initial permeability (30 PI) and the strand speed is chosen to give perfect burnthrough. The sample of plant data for raw-mix permeability is then fed into the system assuming that the strand continues to run at the same constant speed. The accumulated waste is used as a basis for comparison of the performances of the various controlled systems. Performance is presented in terms of waste index (%) which is defined as 100 (waste in given case)/(waste in constant speed case).

Results for the Controlled Cases

With reference to Fig. 4, the results for Control Laws 1 and 2 are very similar. Minimum waste is produced when the control law is based on those sections forming the final 20% of the bed. The minimum value of 55% for waste index is greater than previously published values (Dash, Rose, 1978; Rose, 1980) because of the more realistic smoothing procedure used here to prevent sudden changes in strand speed. Also, this is the first time that a nonlinear model of the process has been used in control system studies of the present type.

The effectiveness of the new control scheme (Control Law 3) is obviously dependent on the extent to which one allows the shift time to be modified by the time error function kt_{ea}. An upper limit was placed on the value of kt_{ea} and the effects of varying this limit are shown in Fig. 4. By comparison, the effect of varying the value of k (with a limit still placed on kt_{ea}) appeared to be less significant but with a "best" value in the region of k = 0.3. The results selected for presentation in Fig. 4 are therefore for k = 0.3.

The net result is a significant reduction in waste index to a value as low as 35%. This occurs when the limit placed on kt_{ea} (i.e. 7.2 sec) is as low as possible consistent with the practical constraint that strand speed cannot be reversed. The flatness of the curves for the new control scheme indicates that the number of sections used in the control law calculation is not specially significant provided that it exceeds 10% of the total (reckoned from the output end).

The main purpose of the work is to develop a procedure (Control Law 3) which improves upon previously reported work (e.g. Control Law 1). The time response of waste index is therefore shown as a differential index, Fig. 5. The modification to the manipulation of strand speed is clearly demonstrated.

CONCLUSIONS

An improved form of previously published control laws for use in feedforward control of a sinter strand has been developed by means of computer simulation. The results indicate that by adopting the new control law, a greater proportion of good quality sinter will be produced.

Compared with previous studies greater realism has been given to the simulation by (1) assuming a nonlinear characteristic for flame-front velocity, and (2) smoothing strand speed changes.

However, absolute numerical values associated with the results must be treated with caution because (1) although 'waste' may be used as a comparative indicator of rejected sinter, no work has yet been carried out to correlate this notional quantity with return-fines produced on plant, and (2) perfect prediction (or measurement) of flame-front velocity is assumed for the feedforward controller.

MORE RECENT INVESTIGATIONS

The weaknesses of the proposed feedforward method lie mainly in the practical difficulties of measuring raw-mix permeability on-line and in formulating a sufficiently accurate, yet simple, model of the process from which time-to-burnthrough can be predicted.

In present practice the plant operator assesses the state of the process from the recording of the temperature of the exhaust gas just ahead of the suction fan and accordingly he makes adjustments to strand speed. Plant records suggest that the delay inherent in this method allows unnecessarily large variations in waste gas temperature and therefore in process efficiency. Recent work has been directed towards the use of self-tuning prediction methods and it has been shown that accurate prediction of waste gas temperature several minutes in advance can be achieved (Kanjilal, Rose, 1982). By inverting the algorithm it is possible to determine for a range of prediction times, the ideal values of strand speed which would yield a steady waste gas temperature. It is envisaged that a feedforward control law in which these ideal speeds are combined and weighted in a manner similar to that described earlier could be used.

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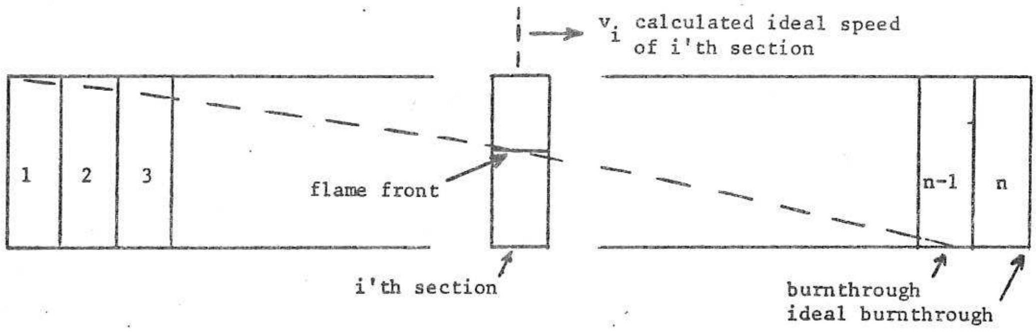

Fig. 1. Sinter bed composed of n lumped sections

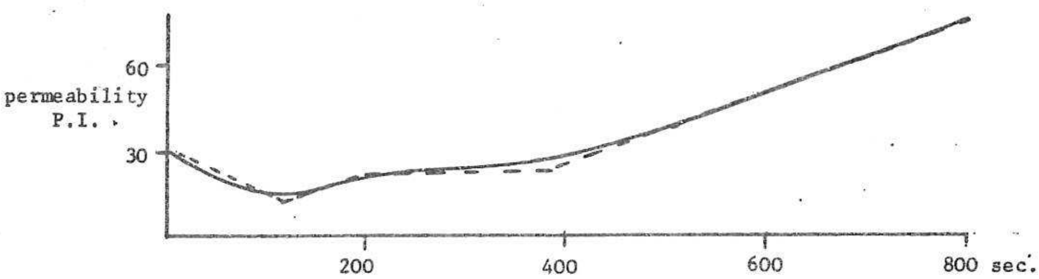

Fig. 2. Typical variation of permeability of a section of bed as it moves along strand

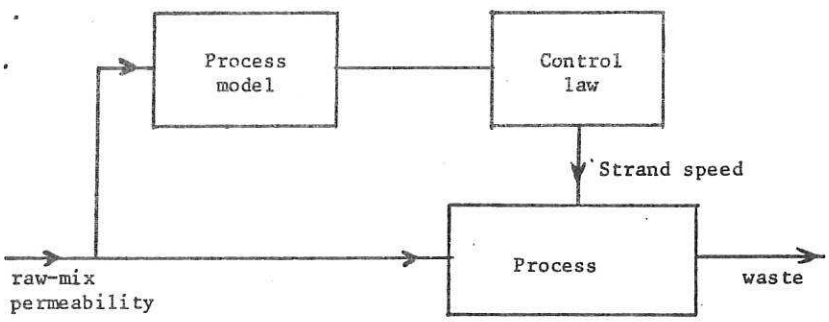

Fig. 3. System block diagram

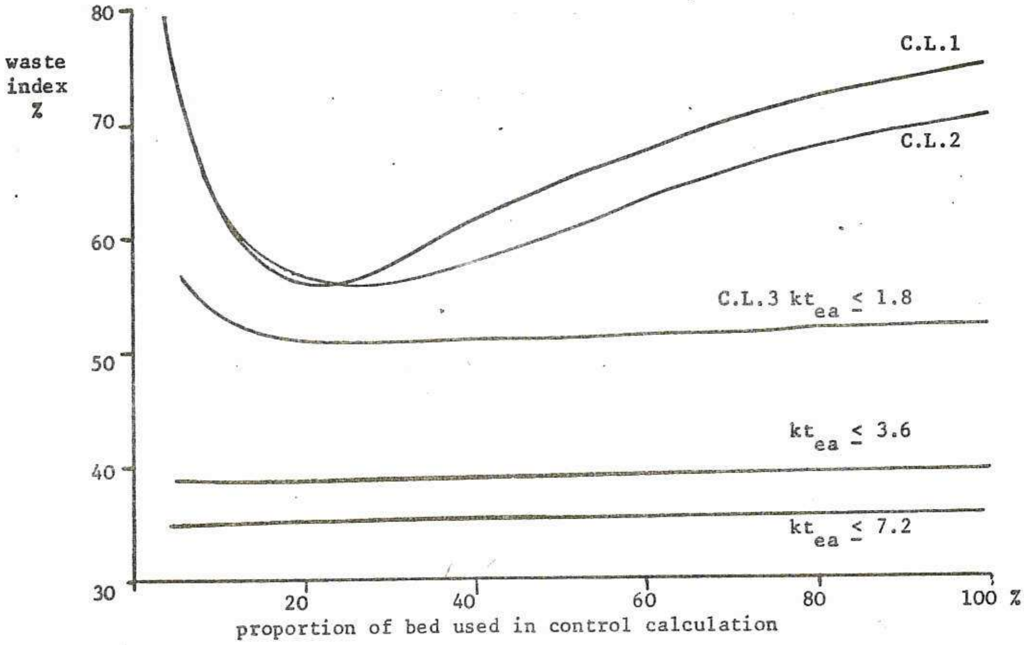

Fig. 4. Improvement in waste index using new control law and effect of varying kt_{ea} limits

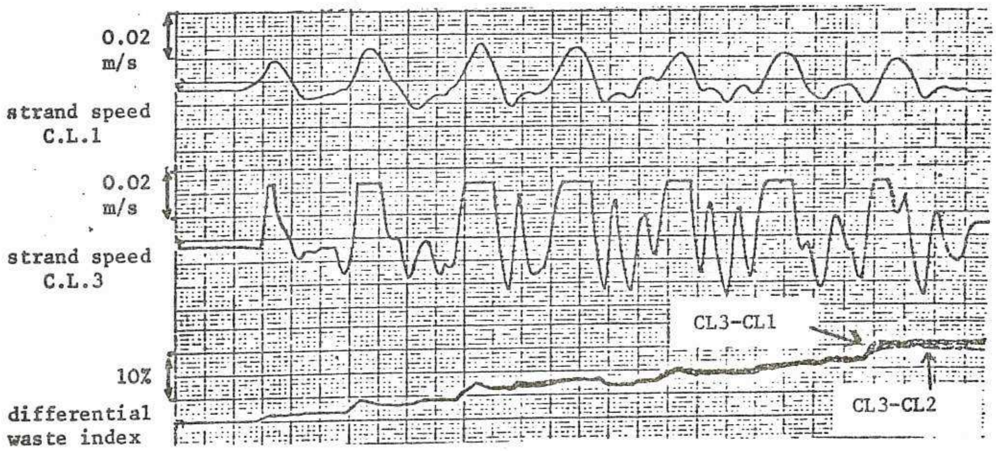

Fig. 5. Strand speed variation for control laws 1 and 3 and improvement in waste index (length of records shown, 108 min)