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Punch velocities during the compaction process

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Velocities achieved by the upper punch of an eccentric tablet press during compaction have been compared with those predicted by equations describing the movement of the punch in an empty die. Up to the point of maximum punch penetration, actual speeds are invariably less than the predicted speed, the magnitude of the deceleration being determined by the machine speed and applied force. As the punch withdraws from the die, its speed can exceed that predicted on theoretical grounds, due to the elastic expansion of the tablet assisting punch ejection.

It is well-known that some tablet formulations are susceptible to changes in the speed at which they are compressed and this may lead to difficulties when, for example, production is transferred from one type of press to another or when the rate of production is changed. Armstrong & Blundell (1985) have shown that a powder which consolidates by fragmentation is less susceptible to speed changes than one whose consolidation mechanism is primarily that of deformation. The latter mechanism does not occur instantaneously and hence if the deforming force is not applied for long enough, tablet quality is adversely affected.

With the introduction of compaction simulators (e.g. Hunter et al 1976), it has become possible to mimic the pattern and rate of punch movement so that, in theory at least, particulate systems can be subjected to a consolidating force whose magnitude changes at the same rate as it would in a conventional press.

Armstrong et al (1983) derived equation 1 which describes the upper punch of an eccentric press as a function of time, and with it introduced the concept of power input. This is derived from the product of the force and the punch speed at the time that force is applied.

$$\frac{dy}{dt} = \omega r \cos\theta \left(1 + \frac{r \sin\theta}{\sqrt{l^2 - r^2\cos^2\theta}}\right) \qquad (1)$$

where ω is the angular velocity of the drive shaft, y is the punch position at time t, r is the radius of the eccentric sheave, l is the length of the eccentric strap, $\theta = 90°$ at maximum punch penetration.

Charlton & Newton (1984) reported a similar equation for an eccentric press and extended their treatment to cover punch movement in a rotary press. However, both the above treatments are theoretical in that they describe punch movement into and out of an empty die. The following work describes a comparative study between theoretically predicted punch movements and those that occur in practice.

MATERIALS AND METHODS

A hand-operated Apex eccentric press was modified by fitting it with a 0·25 hp electric motor, a flywheel (mass approximately 16 kg) and a Kopp variator, so that a speed range of 20 to 160 tablets min^{-1} could be obtained. The upper punch was fitted with strain gauges, and punch movement was monitored by a linear variable differential transformer. After amplification and digitization, transducer signals were stored and manipulated by a BBC Acorn computer. Full details of this are given elsewhere (Blundell 1986).

Tablets were prepared from four directly compressible tablet diluents, namely microcrystalline cellulose (Avicel PH 102, Honeywill and Stein, London), modified starch (Sta-Rx 1500, Colorcon, Orpington), direct compression lactose (Fast-flo, Sheffield) and calcium phosphate (Emcompress, Forum Chemicals, Reigate). The first two substances consolidate primarily by deformation and the last two by fragmentation. 12·5 mm diameter flat-faced punches were used. Punch faces and the die wall were lubricated with a suspension of magnesium stearate in acetone.

RESULTS AND DISCUSSION

Because the computer can be set to accept samples from the transducers at given time intervals, it acts as an accurate clock and the change of force and displacement with time can thus be measured. From the latter, the actual punch speed can be calculated.

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If the speed of rotation of the machine is known, the angular deviation (θ) can be calculated at any given time and hence the theoretical speed and punch displacement can be derived. In this way, the theoretical and actual speed profiles of the punch and corresponding punch displacements can be compared.

Fig. 1 represents the actual and theoretical punch movements when direct compression lactose was compressed at 0·63 rev s^{-1} up to a maximum force of 11·9 kN. The theoretical punch displacements are symmetrical about the point of maximum punch penetration, as predicted by equation 1, as is the displacement of the punch moving into an empty die. The actual displacement is derived from approximately 160 individual signals received over a period of about 0·24 s. Individual data points are therefore not shown, although some symbols are added to assist identification.

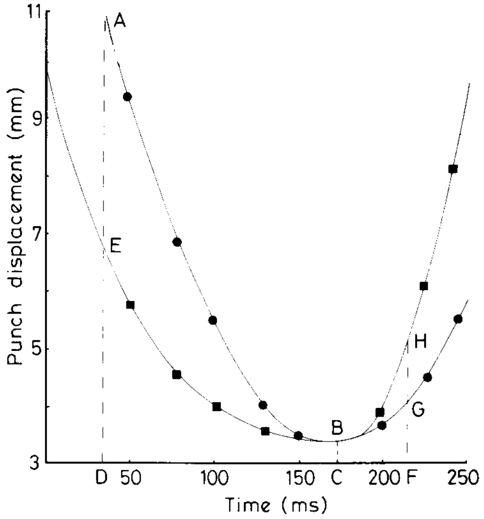

FIG. 1. Actual (■) and theoretical (●) punch displacements plotted as a function of time when compressing Fast-flo lactose. Machine speed, 0·63 rev s^{-1}; maximum force, 11·9 kN. Point D represents the time at which the descending punch exerts a force on the powder and point F is when the ascending punch loses contact with the tablet.

To facilitate comparison between the slopes of the two curves, the minima on each are shown to coincide. This does not actually occur in practice. Punch penetration into the filled die is less than when powder is absent, due to punch and machine frame deformation and the taking up of slack in the bearings of the press, the so-called machine stiffness described by Kennerley et al (1981).

If the curves to the left of the minima are considered, it is seen that throughout these portions of the curves, the punch is travelling slower than predicted by equation 1. This might intuitively be expected. As the descending punch exerts a progressively greater force, it follows that the load on the driving motor increases, thereby causing it to slow down. At relatively low forces, this deceleration is probably imperceptible but, in extreme cases, tablet presses may stop if the load is excessive and many commercial presses have overload release devices to accommodate such a situation.

After the minima have been passed, it might be expected that the curves will coincide, but this is not so. In some cases, the theoretical speed is now less than the actual speed. This is attributed to the elastic expansion of the tablet expelling the punch from the die, and will be discussed later.

The compaction process may be quantified by measuring the maximum force exerted, the work delivered by the press (deBlaey & Polderman 1971) or the power expended (Armstrong et al 1983). In the first two, there is no element of time and so applied force and work will not vary as a function of punch velocity. If power is calculated, the power expenditure differs greatly depending on the method used for the calculation of punch velocity.

Power expenditure to maximum punch penetration can be calculated in three ways.

(i) The overall work done in the compaction process divided by the total time up to maximum punch penetration (t) (formula 1).

(ii) The sum of the products of force (F) and the actual punch velocity (formula 2).

(iii) The sum of the products of force and the theoretical punch velocity (V) derived from equation 1 (formula 3). x is the position of the punch, x_0 is punch position at the first detected force and x_{max} is punch position at maximum punch penetration into the die.

$$\frac{\int_{x=0}^{x_{max}} F.dx}{t} \qquad \text{formula 1}$$

$$\int_{x=0}^{x_{max}} F.\frac{dx}{dt} \qquad \text{formula 2}$$

$$\int_{x=0}^{x_{max}} F.V \qquad \text{formula 3}$$

Table 1 gives the power expended in compressing Emcompress at two forces and two machine speeds, as calculated by the above three formulae. As would be expected, when the machine speed is increased,

Table 1. Total power expended during compression of Emcompress (mean and standard deviation).

Machine speed (rev s^{-1})	Maximum force kN	Power expenditure (W) calculated according to Form. 1	Form. 2	Form. 3
0·36	5·5	9·96	10·37	20·59
	(0·13)	(0·30)	(0·31)	(1·34)
	12·57	16·77	17·33	46·21
	(0·17)	(0·62)	(0·64)	(2·31)
2·63	5·68	17·95	19·34	409·44
	(0·16)	(1·05)	(0·72)	(34·55)
	12·54	30·17	31·96	831·04
	(0·24)	(1·71)	(1·73)	(73·49)

Table 2. Ratio of areas under displacement-time curves interpolated at an applied force of 10 kN, up to maximum punch penetration.

Machine speed (rev s^{-1})	Ratio Avicel	Sta-Rx 1500	Fast-flo lactose	Emcompress
0·36	0·75	0·77	0·77	0·74
0·63	0·73	0·75	0·75	0·75
2·63	0·83	0·89	0·89	0·89

the time over which the work is done decreases and hence calculated power increases. Formulae 1 and 2 give approximately the same values of power, discrepancies being accounted for by electrical noise having an effect on the digitalized values of force and displacement being used in the calculation. Also digitalization causes a rounding up or down of transducer data, and these too will contribute to discrepancies between calculated power values. These effects are magnified when the work term derived from them is divided by short time periods (less than 1 ms) to give power. However, the values calculated with formula 3 are much higher, since the predicted punch velocity is much greater than that which actually occurs.

In an attempt to establish if the substance being compressed had any effect on the punch speed profile, four different solids were compressed at three machine speeds over a force range of 4 to 16 kN. Deceleration is expressed by calculation of the ratio of the areas under the displacement-time curves up to their minima, i.e. with reference to Fig. 1, area EBCD/area ABCD. The greater the deceleration, the lower will be the ratio.

Fig. 2A–D shows these ratios for the four substances (closed symbols). Zero force represents the actual punch movement in an empty die. The fact that this does not vary from substance to substance at any given speed is indicative of the precision of the measurements. Slight changes as the speed is increased can be attributed to inertial effects on the moving parts of the press.

It is seen that deviation from the theoretical displacement pattern increases with increased force, and decreases with increased machine speed in all cases. The influence of the substance can be seen in Table 2, which is obtained by erecting a vertical at 10 kN on Fig. 2A–D, and interpolating the ratio values. In fact, the substance has relatively little effect, except in the case of Avicel compressed at 2·63 rev s^{-1}. It would thus appear that machine parameters, machine speed and force are the major influences on deviations of punch speed from theoretical values. However, it must be borne in mind that the force applied detected by the transducer on the upper punch is determined by the resistance to the punch provided by the powder during consolidation.

The same treatment can be used to investigate those factors which cause deviations from the predicted punch velocity after the minimum in the displacement curve has been passed. With reference to Fig. 1, the ratio of area BCFH/area BCFG is calculated. These ratios are shown in Fig. 2A–D (open symbols) and, as before, zero force represents punch movement in an empty die. A ratio greater than unity implies that the displacement at a given time is greater than that predicted by the integrated form of equation 1, i.e. up to that time, the punch must have exceeded its predicted velocity.

All substances show this behaviour at the lowest speed and the deviation from predicted velocity is greater as the compaction force is increased. This is consistent with the explanation that such deviations can be attributed to elastic recovery in the tablet as the compressing force is removed. The greater the compressing force, the greater will be the extent of elastic recovery.

When compressed at a rate of 0·63 rev s^{-1}, the ratios only exceed unity at forces above about 10 kN, but then rise with increasing compression pressure. At the highest speed studied, no value above unity is obtained. This, too, is indicative of elastic recovery, but it is also a measure of how quickly the system reacts to the removal of the compressing force. Punch acceleration by elastic recovery can only occur if the upper face of the tablet remains in intimate contact with the punch. If the punch is withdrawn from the die at a greater rate than the tablet expands, then tablet expansion will have no effect on punch speed. It is suggested that this occurs in all cases

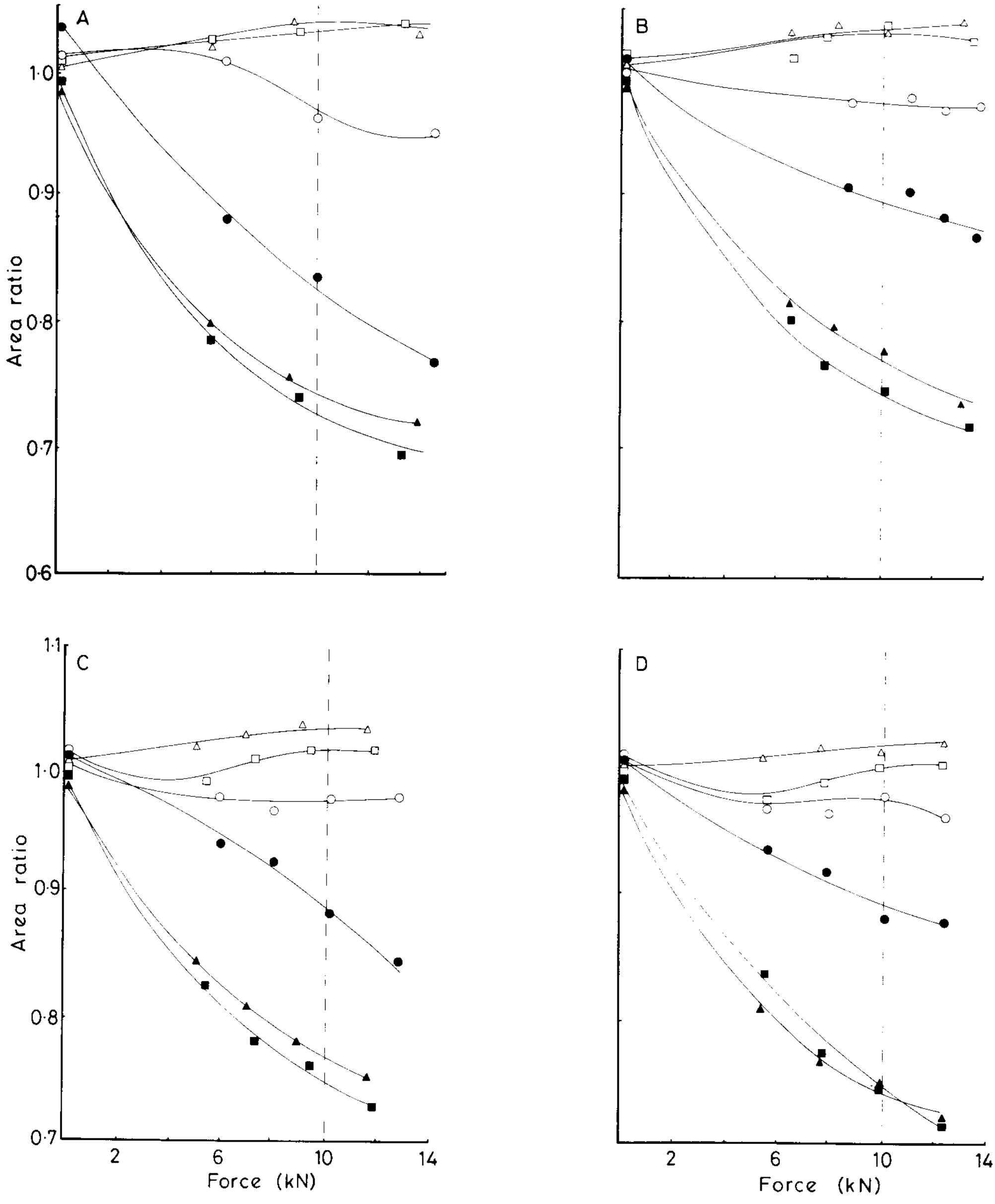

FIG. 2. Ratio of areas under the displacement time curves (for definition see text) as a function of applied force and machine speed. A, Avicel; B, Sta-Rx 1500; C, Fast-flo lactose; D, Emcompress. Machine speeds (rev s^{-1}) ▲ △, 0·36; ■ □, 0·63; ● ○, 2·63. Closed symbols, compressive phase; open symbols, decompressive phase.

where the machine speed is 2·63 rev s^{-1}, and where the speed is 0·63 rev s^{-1}, only at high pressures is elastic recovery great enough to have a detectable effect on the punch.

It is not suggested that these findings constitute a method for measuring the magnitude of elastic recovery of a tablet, since this cannot be assumed to have been completed by the time the punch loses contact with the tablet face. However, they are indicative of the speed at which elastic recovery takes place and further studies in this area would be facilitated by withdrawing the punch at a nominally constant speed, and noting variations in this speed.

Thus the movement of a punch in an empty die can be accurately predicted by equation 1. However, if the die is not empty, the actual movement deviates from that predicted, the magnitude of the deviation being dependent on the applied force, the machine speed and the material being compressed. Also deviations from the predicted punch velocity caused by the above factors will depend on the power of the motor driving the press, in that a more powerful motor will be better able to withstand the decelerating effects caused by the rise in compressing force.

It therefore follows that if simulators are to be used to study the compaction process, the pattern of punch movement fed into the simulators must be adjusted to take these factors into account. Feeding in a uniform pattern of punch movement which is to be used under all circumstances may give rise to misleading results.

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