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Calculation of Punch Displacement and Work of Powder Compaction on a Rotary Tablet Press

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Abstract—To calculate the work of compaction during tableting it is necessary to have accurate values of force and punch displacement. The direct measurement of punch displacement on a rotary press is both costly and complicated but calculated displacements will be in considerable error unless deflections in the press during compression are taken into account. By analysing the physical restraints imposed on the punches during tablet compression, an expression for punch displacement was derived. From preliminary measurements made on the tablet press of machine deflections and punch displacement under static conditions, the terms of this expression were evaluated for dynamic conditions. This analytic solution was then used to determine the true punch displacement and work of compaction from direct measurements of vertical force and turret position.

Energy expenditure during powder compaction has been suggested as a useful means of evaluating the performance of tablet formulations (Nelson et al 1955; Krycer et al 1982). Determination of the mechanical energy used to form a tablet requires the measurement of force as it varies with the distance travelled by the tablet punches during powder compaction. Single station eccentric presses are readily instrumented to measure the axial forces exerted by the upper and lower punches and the distance moved by the upper punch, but, with a few exceptions (e.g. Ho et al 1979; Kaneniwa et al 1984; Armstrong & Palfrey 1987), errors in measured displacement owing to the deformation in the tablet press itself have been ignored. These errors can lead to large errors in calculating values of work of compaction and other parameters such as compact density. Despite this limitation, studies using eccentric presses have provided much information about the mechanical properties of powders and a greater understanding of the compaction process. Nevertheless, an eccentric press cannot reproduce the conditions which obtain on a rotary multi-station press. Compaction on the latter is double-sided whereas on a single-station press, compaction is single-sided only. Moreover, there can be considerable differences in relative punch speed between the low velocities commonly encountered on an eccentric press and the higher velocities possible on a rotary press. Since compact formation depends on time-dependent viscoelastic properties, the speed of the process can have marked effects on compactibility and on tendencies such as lamination, capping and picking which can occur during and/or after ejection of the tablet from the die. Because of the limitations of the eccentric press, it is preferable to carry out research and development studies using a rotary press.

Fully instrumented and computerized rotary presses capable of measuring both force and displacement are now available commercially (e.g. the Manesty Betapress with compression cycle analysis system) but they are very costly. Most research using rotary presses has been limited to measurements of punch force and ejection force. It is relatively easy to instrument a press to measure changes in punch force during a compression cycle, but the measurement of punch displacement poses some formidable problems due to the difficulties of retrieving signals from the moving punches. Walter & Augsburger (1986) instrumented the upper and lower punches on a Colton 216 rotary press to measure both force and displacement. Data were collected from the rotating turret through an eight channel mercury swivel system. Since displacement data were obtained through an umbilical cord that was designed to break away following compression, measurements were restricted to a single compression cycle. Because of the expense and complexities involved in instrumenting a rotary press to measure punch displacement, particularly under normal operating conditions, it would be advantageous if accurate estimates of punch displacement could be obtained by calculation or by some other indirect method. Rippie & Danielson (1981) and Charlton & Newton (1984) calculated punch displacement from the profile of the punch head and machine dimensions but did not take machine deflections into account. Since consolidation of powders into tablets occurs over very small distances, accurate estimates of machine deflection are essential for the accurate determination of punch displacement and thence for the calculation of work of compaction.

In this paper, the machine deflections in a rotary press were measured in a series of preliminary experiments. The data obtained were used in an equation developed from a theoretical analysis of punch displacement to calculate the true punch displacement under actual tableting conditions.

Recent years have seen increasing use by the pharmaceutical industry of microprocessor controlled powder compaction simulators (Hunter 1983). These simulators are capable of reproducing the upper and lower punch displacement-time profiles of any given tablet press. However, unless the simulator is programmed to give the true punch displacement the results of simulated compactions may be subject to considerable error. The true punch displacement must either be measured directly for each particular press or calculated as described in this work.

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Materials and Methods

The rotary tablet press was a Manesty Betapress from which the hopper and feed frame were removed. The tooling consisted of one die with 1/2″ (1·270 cm) Manesty flat-faced upper and lower punches. The remaining fifteen die stations were blanked off, and the precompression rolls were adjusted so that no force was applied to the punches.

Upper and lower punch forces

On a rotary tablet press, force is applied to powder, confined within a die, by upper and lower punches as they travel between two pressure rolls. The roll pin supporting the upper pressure roll was removed and replaced by a pin specially fabricated to permit the incorporation of strain gauges in a full Wheatstone bridge configuration arranged to measure the vertical component of the applied force only. Before installation the roll pin was calibrated using a mechanical stress-strain analyser.

Strain gauges mounted on the cross beam supporting the lower pressure roll were used to measure the lower punch force. These strain gauges were calibrated against the instrumented upper roll pin. Strain indicators were used to amplify and filter the strain signals from the instrumented upper roll pin and lower cross beam. The analogue voltage signal outputs from the strain indicators were converted to a digital signal using a fast A/D converter interfaced with an Apple II Plus computer. Data could be collected at a maximum rate of about 4500 readings s^{-1} for the 2 channels. During an experiment the digital information was transferred from the A/D converter to the computer's random access memory and saved on a floppy disk for permanent storage if required. Data collection during a compression cycle was triggered when a magnet rotating with the turret passed by a magnetic reed switch fixed to the mainframe of the machine. A second reed switch was used to indicate the point at which the upper and lower punches were aligned with an imaginary vertical line passing through the centres of the two pressure roll support pins. This corresponds to the point at which the punch faces make their closest approach to one another in an empty die.

Punch displacement

During the compression cycle, the slope at the point of contact for both the punch head and the pressure roll must be the same. Using this relationship we derived an equation similar to that of Rippie & Danielson (1981) and of Charlton & Newton (1984). Calculated displacements, however, as pointed out by Armstrong & Palfrey (1987), only describe punch movement into and out of an empty die, i.e. the equation assumes that the machine does not deflect when under load. Preliminary experiments showed that machine deflection and recovery during compression and decompression is considerable relative to tablet thickness.

To determine the distance, D, between two opposing punch faces during compression, it is necessary to examine the geometry of the press (Fig. 1). At any given turret position when the punches are pressed against their respective pressure rolls, the machine is physically constrained such that the following relationship is imposed:

$$D_{AA'} + D_{M1} + D_{M2} = D_{P1} + D_{P2} + D_{PUN1} + D_{PUN2} + D \quad (1)$$

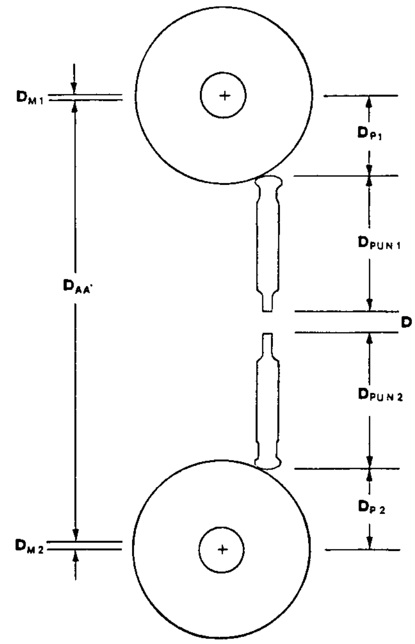

FIG. 1. Geometry of punches and pressure rolls showing the machine deflections, D_M, during compressive loading.

Where:

$D_{AA'}$ is the vertical separation between the axes of the upper and lower pressure rolls when no force is applied to them. (This distance is set before compression by the tablet thickness adjust gear and remains constant when the machine is in operation);

D_{M1} is the vertical deflection of the machine in an upwards direction when a vertical force is applied. (D_{M1} includes all displacements and deformations in the upper pressure roll assembly and the upper punch. D_{M1} is positive when the distance D is increased);

D_{M2} is the vertical deflection of the machine in a downwards direction when a vertical force is applied. (D_{M2} includes all displacements and deformations in the lower pressure roll assembly and the lower punch. D_{M2} is positive when D is increased);

D_{P1} is the vertical distance between the upper roll axis and a fixed reference point on the upper punch. (This term reaches its maximum value when the turret position is such that the centres of the punches lie directly between the axes of the two rolls);

D_{P2} is the vertical distance between the lower roll axis and a fixed reference point on the lower punch. (It reaches its maximum value at the same turret position as D_{P1});

D_{PUN1} is the vertical distance from the reference point on the upper punch to the punch face when no force is applied. (If the reference point is defined as the top of the upper punch head then D_{PUN1} is the length of the upper punch);

D_{PUN2} is the distance between the reference point and the punch face on the lower punch when no force is applied.

The position of the die table is specified by fractions of a revolution, fr, measured from the point when the vertical axis of the punches of interest fall in line with an imaginary vertical line connecting the axes of the two pressure rolls. This corresponds to the point where the punches make their closest approach to one another in an empty die. Before this point, fr is negative.

It is convenient to sum the terms D_{M1} to D_{M2}, D_{P1} to D_{P2}, and D_{PUN1} to D_{PUN2} to form the new values D_M, D_P, and D_{PUN}. By substituting these values into equation 1 and then rearranging the terms, an expression for D is obtained:

$$D = D_{AA'} + D_M - D_P - D_{PUN} \quad (2)$$

The derivative of equation 2 is obtained by differentiating it with respect to the independent variables which affect the terms on the right hand side of the equation. The variables are fr, the vertical and horizontal components of force applied to the upper pressure roll, F_{V1}, and F_{H1}, respectively, and the vertical and horizontal components of force at the lower pressure roll, F_{V2}, and F_{H2}, respectively. It is necessary to determine which of these five variables are independent. The geometry of the machine is such that the punch heads can only press against their corresponding pressure rolls at unique turret positions. At the point of contact, the tangent of the punch head and the tangent of the pressure roll must be the same. Therefore, the horizontal force at each pressure roll is a dependent variable since its magnitude depends on the vertical force and the turret position. Furthermore, because of the glancing angle with which the punch heads strike the pressure rolls, F_{H1} and F_{H2} are very small relative to F_{V1} and F_{V2}. Hence, the three independent variables are fr, F_{V1}, and F_{V2}. The force F_{V1} is positive when it is acting upwards, and F_{V2} is positive when the force is acting downwards.

When the tablet press is in operation, the distances $D_{AA'}$, and D_{PUN} are fixed. By taking the derivative of equation 2 with respect to the three independent variables, equation 2 becomes:

$$\begin{aligned} dD = {} & \{(\partial D_M/\partial fr)_{FV1,FV2} - (\partial D_P/\partial fr)_{FV1,FV2}\}dfr \\ & + \{(\partial D_M/\partial F_{V1})_{fr,FV2} - (\partial D_P/\partial F_{V1})_{fr,FV2}\}dF_{V1} \\ & + \{(\partial D_M/\partial F_{V2})_{fr,FV1} - (\partial D_P/\partial F_{V2})_{fr,FV1}\}dF_{V2} \quad (3) \end{aligned}$$

Each term in equation 3 is a partial derivative with respect to one of the variables with the other two variables fixed.

Machine deflection D_M

To estimate the relationship between applied vertical force and the total machine deflection in the vertical direction, feeler gauges, selected to give a range of thicknesses, were compressed between the opposing flat-faced punches under static conditions. Since standard feeler gauges cannot be inserted between the punch faces in a punch and die assembly, the die was removed from the die table and the feeler gauges were cut to fit the die cavity. The turret position was set so that the centres of the upper and lower roll pins and the vertical axes of the upper and lower punches were vertically aligned. This constrains the machine such that the distance between the opposing punch faces, as set by the feeler gauges, must be equal to the total machine deflection. A linear variable displacement transducer (LVDT, Sangamo DG5) was mounted on the mainframe of the machine with its variable arm resting on the top surface of the upper pressure roll so as to measure the vertical deflection of the upper pressure roll independently. The contraction of the upper punch under load can be determined from its dimensions and the modulus of elasticity of steel. The difference between D_M and the deflection of the upper roll assembly, including the contraction of the upper punch, D_{M1}, is equal to the deflection of the lower pressure roll assembly and the deformation of the lower punch, D_{M2}. Fig. 2 shows the total, upper, and lower deflection versus the applied vertical force. The upper roll deflects linearly with the vertical force and represents about 35% of the total deflection in the press. The remaining 65% of the machine deflection occurs in the lower part of the press and varies linearly with respect to applied force with a marked change in the slope at approximately 2·3 kN. The machine's vertical deflection in response to an applied vertical load is given by:

$$D_M = K_U^{-1} F_{V1} + K_{L1}^{-1} F_{V2} \text{ for } F_{V2} < 2{\cdot}3 \text{ kN}, \quad (4a)$$

$$D_M = K_U^{-1} F_{V1} + K_{L2}^{-1} F_{V2} + (K_{L2}^{-1} - K_{L1}^{-1}) \times 2{\cdot}3 \text{ kN} \quad \text{for } F_{V2} \geqslant 2{\cdot}3 \text{ kN} \quad (4b)$$

where K_U is Hooke's constant of proportionality for the upper pressure roll, K_{L1} is the deflection constant for the lower pressure roll and crossbeam for forces less than 2·3 kN, and K_{L2} the deflection constant for the lower pressure roll and crossbeam for forces greater than 2·3 kN.

The value of K_U^{-1} is $8{\cdot}5 \times 10^{-7}$ cm N^{-1}. The constants K_{L1}^{-1} and K_{L2}^{-1} equal $3{\cdot}3 \times 10^{-6}$ cm N^{-1} and $1{\cdot}5 \times 10^{-6}$ cm N^{-1}, respectively.

The above experiment was repeated at different turret positions to determine how the turret's position affects the machine deflection. To set the turret position, the ejection half of the lower cam track was removed leaving the other half of the cam track to act as a stop for the head of an extra lower punch placed two stations before the experimental test station. The die table was hand turned using the flywheel to bring the extra lower punch firmly against the stop. Feeler gauges of different thicknesses placed between the stop and the extra punch head were used to vary the position of the lower punch head in the experimental test station relative to the lower compression roll.

The results from these experiments indicate that the constants K_U, K_{L1}, and K_{L2} do not change significantly for different turret positions. It was concluded, that on a Betapress, D_M is independent of the turret position and can be expressed as a function of the applied vertical forces as

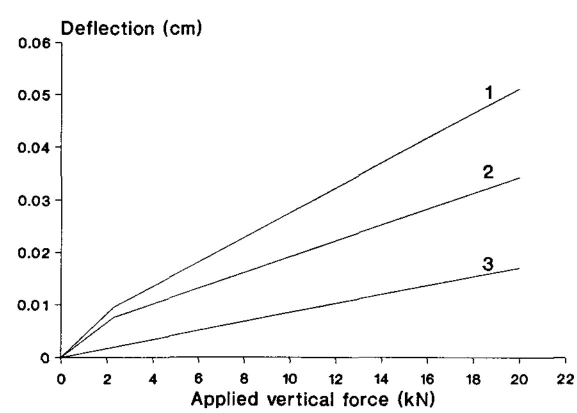

FIG. 2. Machine deflections, D_M, as a function of applied vertical force, F_V. Curve 1: total deflection; curve 2: lower deflection; curve 3: upper deflection.

defined in equations 4a and 4b. Differentiating these equations by the vertical forces and the turret position gives:

$$(\partial D_M/\partial F_{V1})_{fr,FV2} = K_U^{-1} \quad (5)$$

$$(\partial D_M/\partial F_{V2})_{fr,FV1} = K_L^{-1} \quad (6)$$

$$\text{and } (\partial D_M/\partial fr)_{FV1,FV2} = 0 \quad (7)$$

where $K_L = K_{L1}$ for $F_{V2} < 2{\cdot}3$ kN,
$= K_{L2}$ for $F_{V2} \geq 2{\cdot}3$ kN

Punch displacement with respect to the roll axes

Equation 3 contains three partial derivatives of D_P with respect to the turret position, and to both the upper and lower vertical forces. In practice, however, it is difficult to isolate the effects of the upper force from those of the lower force on D_P since these forces cannot easily be set independently. For this reason, the partial derivatives with respect to the upper and lower forces were simplified to a partial derivative with respect to one vertical force F_V where $F_V = (F_{V1} + F_{V2})/2$. During an actual tablet compression, the upper and lower forces are almost equal and therefore this approximation is not expected to incur any significant errors. The new partial derivatives containing D_P are:

$$(\partial D_P/\partial fr)_{FV} = (\partial D_P/\partial fr)_{FV1,FV2} \quad (8a)$$

$$(\partial D_P/\partial F_V)_{fr} = (\partial D_P/\partial F_{V1})_{fr,FV2} + (\partial D_P/\partial F_{V2})_{fr,FV1} \quad (8b)$$

By holding the distances D_M, D_{PUN}, and D constant under static conditions and then varying the distance $D_{AA'}$ to impose a force, D_P can be estimated as a function of fr at a fixed force. By physically constraining the system in this manner, a change in $D_{AA'}$ will result in a corresponding change in D_P. The distance $D_{AA'}$ was varied by turning the tablet thickness gear which causes the lower crossbeam to be raised or lowered. An LVDT mounted on the mainframe of the machine with its variable arm resting on the centre of the crossbeam, was used to measure the vertical position of the beam. Since the machine deflection D_M is only a function of force, applying a fixed force to the punches and pressure roll assemblies results in a fixed deflection. The distance D was held constant by compressing a 1·267 cm flat-faced steel tablet between the two punch faces. A range of turret positions was set statically using the same method used in setting the turret to estimate D_M. At each specific turret position, the tablet thickness gear was turned to impose the desired force. The readout from the LVDT was recorded at each turret position. The results from these experiments were stored in an array. The differential of D_P with respect to the turret position was obtained using a polynomial fit program. The curves of $(\partial D_P/\partial fr)_{FV}$ vs fr did not differ significantly for different fixed vertical forces and are well approximated by a straight line, Fig. 3.

The final term to be estimated is $(\partial D_P/\partial F_V)_{fr}$ which represents the change in D due to horizontal shifts in the machine. These shifts occur mainly at the two pressure rolls and the lower crossbeam. To estimate the term $(\partial D_P/\partial F_V)_{fr}$, the steel tablet was compressed under operating conditions but with the ejection cam removed. This physically constrained the machine so as to maintain a constant distance between the opposing punch faces thereby setting dD equal to zero. Under these conditions, the upper and lower punches

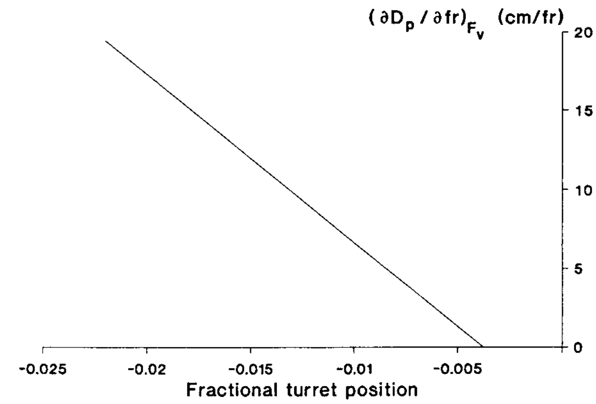

FIG. 3. Changes in D_P with turret position, fr, at a fixed vertical force, F_V, vs fractional turret position.

are subjected to the same compressive loading and therefore $dF_{V1} = dF_{V2} = dF_V$. By substituting dF_V for dF_{V1} and dF_{V2} into equation 3 and substituting equation 8a and 8b into equation 3 the following expression is obtained:

$$(\partial D_P/\partial F_V)_{fr} = (\partial D_M/\partial fr)_{FV1,FV2} + (\partial D_M/\partial F_{V1})_{fr,FV2} + (\partial D_M/\partial F_{V2})_{fr,FV1} - (\partial D_P/\partial fr)_{FV}/(dF_V/dfr) \quad (9)$$

Each term on the right hand side of equation 9 is known from previous measurements except for (dF_V/dfr) which was determined by compressing the steel tablet under dynamic conditions to provide a family of force vs turret position curves with different peak forces up to 60 kN. Fig. 4 shows a representative series of these curves. A curve-fitting program was then used to obtain the differential of force with respect to the turret position, (dF_V/dfr). Equation 9 was evaluated and the values for $(\partial D_P/\partial F_v)_{fr}$ were stored in an array. Fig. 5 shows plots of $(\partial D_P/\partial F_V)_{fr}$ vs F_v at various fixed turret positions.

Unfortunately it is difficult to obtain information about $(\partial D_P/\partial F_V)_{fr}$ for turret positions less than $fr = -0{\cdot}020$ since the force vs fraction curves required would give a peak force exceeding the capacity of the machine. Therefore, outside the region in which $(\partial D_P/\partial F_V)_{fr}$ is defined, this term must be extrapolated. In practice, the inaccuracies which this entails are small since this term is not significant compared with the other terms. For turret positions greater than $fr = -0{\cdot}015$, the dominant term is $(\partial D_P/\partial fr)_{FV}$.

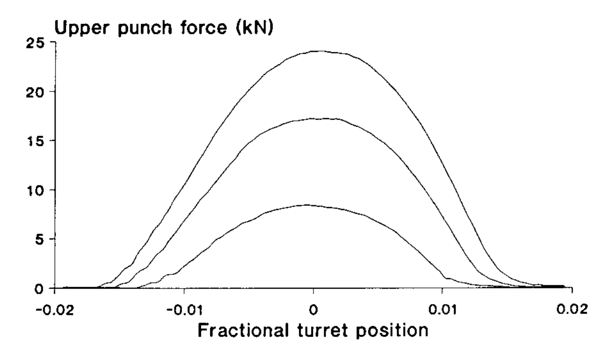

FIG. 4. Representative upper punch force, F_{V1}, vs fractional turret position, fr, curves for the compression of a steel tablet under dynamic conditions.

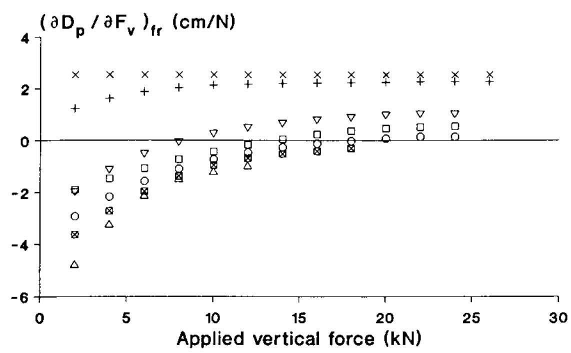

FIG. 5. Change in D_P with applied vertical force, F_V, at fixed fractional turret positions, fr, vs applied vertical force. Key: fr, x, >-0.0035; +, -0.004; ▽, -0.006; □, -0.008; ○, -0.010; ⊠, -0.012; △, -0.014.

By substituting the results from equations 5, 6, 7, 8a, and 8b into equation 3, and using the arrays for $(\partial D_P/\partial fr)_{FV}$ and $(\partial D_P/\partial F_V)_{fr}$, the solution for punch displacement is given by:

$$dD = K_U^{-1}\, dF_{V1} + K_L^{-1}\, dF_{V2} - (\partial D_P/\partial fr)_{FV} dfr - (\partial D_P/\partial F_V)_{fr}\, dF_V \qquad (10)$$

Displacement and work

The change in D when the machine rotates between the turret positions frA and frB is D_{AB}, and is calculated by integrating equation 10:

$$D_{AB} = \int_{frA}^{frB} dD = \underset{(1)}{\int_{F_{V1}A}^{F_{V1}B} K_U^{-1}\, dF_{V1}} + \underset{(2)}{\int_{F_{V2}A}^{F_{V2}B} K_L^{-1}\, dF_{V2}} \underset{(3)}{- \int_{frA}^{frB} (\partial D_P/\partial fr)_{FV}\, dfr} \underset{(4)}{- \int_{F_VA}^{F_VB} (\partial D_P/\partial F_V)_{fr}\, dF_V} \qquad (11)$$

where F_VA is the vertical force experienced when the punch is at the turret position frA, and F_VB is the vertical force at turret position frB.

The vertical machine deflection, term (2) in equation 11, depends on the applied vertical force only and is independent of the turret position. Terms (3) and (4) are determined from the arrays of $(\partial D_P/\partial fr)_{FV}$ and $(\partial D_P/\partial F_V)_{fr}$.

To estimate the work done in forming the tablet (work of compaction or compression energy) W_{AB}, between the turret limits frA and frB, the following integrals are evaluated:

$$W_{AB} = \underset{(1)}{- \int_{F_{V1}A}^{F_{V1}B} K_U^{-1}\, F_{V1}, dF_{V1}} \underset{(2)}{- \int_{F_{V2}A}^{F_{V2}B} K_L^{-1}\, F_{V2}, dF_{V2}} + \underset{(3)}{\int_{frA}^{frB} F_V (\partial D_P/\partial fr)_{FV}\, dfr} + \underset{(4)}{\int_{F_VA}^{F_VB} F_V (\partial D_P/\partial F_V)_{fr}\, dF_V} \qquad (12)$$

Again, term (2) in equation 12 depends only on the vertical forces at frA and frB.

Software computer programs

The analyses and plots required to give the changes in punch displacement with vertical force and turret position together with the corresponding values of work of compaction were performed by programs written for the Apple II Plus computer. In addition, the compression cycles (F_V vs fr curves) were analysed to give the time to reach fr = 0, (compression time), the peak offset time, the peak pressure and the decompression time.

Materials and methods

Samples of spray dried lactose (Foremost) calcium phosphate (Emcompress, Mendell) and microcrystalline cellulose (Avicel PH 102, FMC) were mixed with 0·5% w/w magnesium stearate (Mallinckrodt) and compressed on the instrumented press. Data were collected and analysed for tablets prepared over a range of peak pressures and turret speeds. The terms $D_{AA'}$, D_{PUN1} and D_{PUN2} in equation 1 were fixed by the thickness setting selected and the choice of punches and remain constant during compression. At the thickness setting selected, the required peak pressure was obtained by hand filling the die cavity with a sufficient amount of the lubricated direct compression agent. Ridgway Watt (1983) has shown that the Betapress accelerates to constant speed over a comparatively small fraction of a turret revolution. To ensure that compression took place at the selected operating speed, the press was started with the active tooling station at a preset position from just before the maximum depth of fill position. The tablets were weighed immediately after ejection.

Results and Discussion

A composite of upper punch force vs turret position curves for, Avicel, Emcompress, spray-dried lactose and steel are plotted in Fig. 6. The compression and decompression phases of the compression cycle for the incompressible tablet of steel represent machine deflections and recovery, respectively. Since the decompression curves for each of the three direct compression agents almost coincide with that of steel, it is apparent that any elastic recovery by the tablets during decompression is small relative to machine recovery. During the compression phase, however, marked differences are apparent in the force vs fraction curves. Avicel, which has a low bulk density relative to the other two materials, shows a broader compression profile with a long leading edge. These differences are exemplified by the compression times, (t_{COMP}), given in Table 1. For each material, t_{COMP} increases with increasing pressure but the times become similar for a given

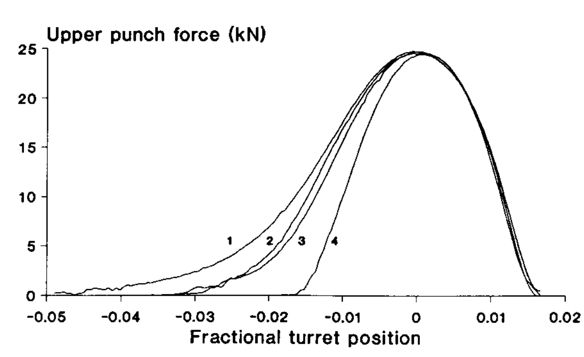

FIG. 6. Upper punch force, F_{V1}, vs fractional turret position, fr, for 1, Avicel; 2, spray dried lactose; 3, Emcompress; 4, steel.

Table 1. Compression times, peak offset times and work of compaction[a].

Peak pressure (MPa)	mass (g)	t_{comp} (ms)	t_{comp} (ms.g^{-1})	Peak offset (ms)	Work of compaction (Nm g^{-1})
Avicel					
70	0·541 (0·3)[b]	37·0 (2·6)	72·0	2·85 (6·8)	22·7 (3·9)
140	0·653 (0·9)	42·6 (0·7)	65·2	1·42 (8·2)	33·2 (3·1)
210	0·715 (0·4)	44·5 (0·6)	62·2	0·54 (26)	39·0 (1·4)
Emcompress					
70	0·754 (0·4)	27·0 (3·1)	35·8	0·37 (74)	6·1 (3·2)
140	0·860 (0·5)	28·6 (1·1)	33·3	0·33 (41)	9·6 (3·0)
210	0·945 (0·4)	32·7 (1·6)	34·6	0·33 (49)	13·1 (3·9)
Spray-dried lactose					
70	0·532 (0·6)	23·3 (2·6)	43·8	1·74 (7·9)	8·7 (4·1)
140	0·619 (0·5)	27·8 (0·8)	44·9	0·93 (24)	15·7 (2·1)
210	0·681 (0·3)	30·2 (0·8)	44·3	0·83 (16)	22·0 (2·7)

[a] Turret revolution time 0·88 s.
[b] Coefficients of variation (per cent); n = 10.

material when normalized for tablet mass. The normalized results show that (t_{COMP}) is shortest for Emcompress and longest for Avicel.

Another feature of the compression curve is that for each direct compression agent, the peak force is reached before fr = 0, whereas for steel the peak force corresponds approximately to fr = 0. The differences between (t_{COMP}) and the time to reach peak pressure are reported in Table 1 as peak offset time which appear to be a characteristic of the compaction behaviour of the material. For Emcompress the peak offset times are about 0·3 ms and appear to be independent of peak pressure. Peak offset times become highly variable at times less than 1 ms; values of less than about 0·5 ms are not significantly different from the values for steel. For Avicel the times range from about 3 ms at a peak pressure of 70 MPa to about 0·5 ms at a peak pressure of 210 MPa. The peak offset times for spray-dried lactose decrease from 1·7 ms at 70 MPa to about 0·9 ms at 140/210 MPa. The results suggest that at all three pressures, Emcompress behaves increasingly like an incompressible solid as the peak pressure is approached during the compression cycle. At 70 MPa the peak offset times for Avicel and spray-dried lactose indicate that stress relaxation is occurring before fr = 0, while at 140 MPa stress relaxation is still evident for Avicel. Peak offset times have been discussed by Rippie (1987) and are noted here since they demonstrate the ability of the present system to detect and measure events taking place during the very short compression cycle times on the Betapress.

Typical displacement/deflection curves for the compression of spray-dried lactose are shown in Fig. 7a. The numbers on the curves correspond to the terms indicated in equation 11. Curve 3 shows what the punch displacement during compression would be if no deflections occurred in the press, and is similar to the curve obtained by calculation from machine and punch head dimensions for punch displacement into an empty die. Curve 2 shows the vertical deflections in the machine; curve 4 gives the changes in D_P due to horizontal shifts in the pressure rolls and the lower cross-beam during compression. The net punch displacement, D, curve 1, becomes increasingly negative as the opposing punch faces penetrate further into the die. Maximum penetration is reached before fr = 0 and D becomes constant.

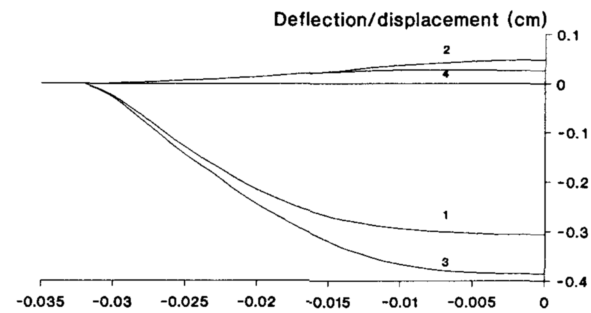

FIG. 7a. Machine deflection/punch displacement, D, vs fractional turret position, fr, for the compression of spray dried lactose at a maximum peak force of 140 MPa and a turret revolution time of 0·88 s. Curve 1 is the calculated punch displacement. Curves 2, 3 and 4 are machine deflections calculated according to the corresponding terms in eqn. 11.

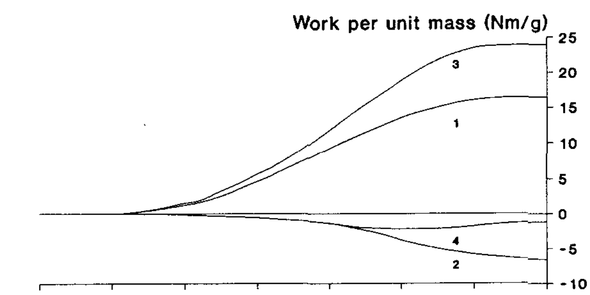

FIG. 7b. As Fig. 7a, except the curves represent work per unit mass vs fractional turret position, fr, for the compression of spray dried lactose. Curve 1 is the calculated work of compaction and curves 2, 3 and 4 are calculated according to the corresponding terms in eqn 12.

Curves showing the change in work (normalized for tablet mass) with fractional turret position for spray dried lactose are shown in Fig. 7b where the curves are numbered according to the terms in equation 12. Positive signs indicate work done by the press on the powder while negative signs indicate work done on the press. Table 2 records the values of displacements calculated for the three direct compression agents at a peak pressure of 140 MPa together with the

Table 2. Punch displacement, machine deflections and work during tablet compression[a].

	Avicel	Emcompress	Spray Dried Lactose
Punch displacement (cm)[b] (machine deflections (cm)[b]			
1	−0·94 (1·5)[d]	−0·34 (3·1)	−0·31 (2·5)
2	0·051 (2·7)	0·051 (3·4)	0·051 (1·8)
3	−1·019 (1·5)	−0·410 (2·6)	−0·390 (1·9)
4	0·030 (1·5)	0·024 (2·0)	0·028 (2·4)
Work (Nm g^{-1})[c]			
1	33·2 (3·1)	9·6 (3·0)	15·7 (2·1)
2	−6·0 (5·3)	−4·7 (6·3)	−6·5 (3·5)
3	40·8 (3·5)	14·7 (3·6)	23·3 (2·1)
4	−1·6 (3·7)	−0·4 (15)	−1·2 (10)

[a] Turret revolution time 0·88 s; peak pressure 140 MPa.
[b] Numbers correspond to terms in eqn. 11.
[c] Numbers correspond to terms in eqn. 12.
[d] Coefficients of variation (percent); n = 10.

corresponding values of work normalized for tablet mass. The work of compaction increases with increase in peak pressure and, for a given peak pressure, varies widely between the three test materials with Avicel having the highest and Emcompress the lowest values (Tables 1, 2). The results show that large errors will occur in calculated punch displacement and hence work of compaction if machine deflections under dynamic conditions are not taken into account.

The procedures described provide a relatively simple and inexpensive method of estimating punch displacement from the applied vertical force and the turret position on a rotary tablet press. Interfacing the press with a personal computer enables the data to be collected, processed and stored ready for subsequent analysis.

The data reported in this paper were obtained from the compression of single tablets using a press from which the hopper and feed-frame had been removed. The system is also capable of operating with the hopper and feed-frame. The computer can be programmed to collect data for every compression or for regularly spaced compressions as required; the number of compression cycles for which data can be collected is limited only by the available memory. Data collection using a complete set of tooling is also possible. Only those materials having a low bulk density, such as Avicel, are likely to cause problems where the long leading edge of the compression cycle (Fig. 6) may overlap with the decompression phase at the preceeding station. Nevertheless, the forces involved at this early stage of compression are low and errors in calculated work of compaction will be small. The precompression rolls on the Betapress could be used to reduce the leading edge but for a complete analysis this would require instrumenting the roll pins of the upper and lower precompression rolls in order to measure the applied vertical force.

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