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# ISOLATION OF DENSIFICATION REGIONS DURING POWDER COMPRESSION

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## ABSTRACT

An instrumented single punch tablet press has been used to monitor the deformation behavior of materials. Lubricated excipients were compressed to the same maximum punch penetration in a constant fill volume and the densification process was followed. The densification of the powder to form a tablet and the corresponding pressures generated in the die were monitored by the instrumentation. The sampling rate per channel was one data point every 0.5 millisecond in a 1.02 second event. Plots of the densification, ln (1 / porosity) versus upper punch pressure in the die, were generated for each tablet formation. The densification plots have six regions which can be isolated based on the upper punch movement in the die. A material's deformation behavior can be described by the densification and pressure changes occurring in the various regions.

## INTRODUCTION

Instrumented single punch tablet presses have been used to monitor the deformation process of powders during compression (1, 2, 3). The dynamic measurement of material densification is related to the formation of the tablet and the resulting tablet properties. The porosity of the tablet results from the extent to which materials are deformed by the pressure distributions in the die. Tablet porosity is dependent on each material's resistance to fracture and deformation but also on the specific details of the deformation process (i.e., extent of friction, temperature, compression cycle). The Heckel relationship (4, 5) between powder densification (ln (1 / porosity)) to pressure generated during compression has been used to describe the deformation mechanisms of excipients and drug products (6, 7). The Heckel plot has been a useful formulation tool in comparing compression properties of granulations made with different binders (6).

The Heckel plot obtained for materials depends on the experimental techniques used (10). Researchers have reported limitations of the Heckel relation in predicting the deformation mechanisms of powders (3, 8, 9). In comparing materials with different deformation mechanisms, the exact point of measuring the volume of the compact will affect the degree of void reduction (i.e., at pressure measurement versus out of die measurement) (4). The particle geometry (7), the particle size (5, 12), the molecular weight (13), the material history and processing, the initial die filling (8), the die size (9), the punch velocity (11), and the type and degree of lubrication of punches and die can influence the degree of densification. The values of the compression parameters will be different depending on the experimental conditions chosen. The Heckel method of monitoring densification and pressure is not a limitation but a sensitive tool to evaluate formulation processing of a drug product.

Duberg and Nystrom monitored tablet formation using an instrumented single punch press and applied the Heckel relationship to characterize three phases in the compression cycle (14). The fill weight for each material was adjusted to produce a thickness of 0.3 cm at maximum compaction load. The punch faces and the die wall were lubricated with a 1% magnesium stearate-ethanol suspension. The material was hand filled and compressed to 150 MPa. The phases were separated based on a pressure interval. Phase I (2 - 50 MPa) was shown to evaluate the fragmentation behavior of the materials. Phase II defined as 40 - 100 MPa was shown to reflect the total deformation ability of the material. Phase III was defined and evaluated by denoting if the minimum porosity was reached at a time event significantly different from the time of maximum load. Both the plastic and elastic deformation behaviors were obtained by evaluating this decompression phase (15).

This paper proposes a technique to separate the Heckel densification plot into six regions based on the upper punch movement in the die. A material's deformation behavior can be described by the densification and pressure changes occurring in the six regions. The study involves a comparison of the densification process of lubricated excipients compressed with a constant fill volume. The surface area is constant for the densification process and the role of friction and lubricants can be evaluated. A series of compression cycles with different maximum punch strokes was studied. In production, materials are compressed in terms of tablet hardness using different maximum punch strokes (Figure 3). The densification data presented in this paper represent compression to the same tablet thickness or the same maximum punch stroke (Figure 4). Deformation and friction parameters can be used to quantitate the differences among the materials in the six regions. A qualitative comparison of the densification process for the lubricated excipients is presented.

## MATERIALS

Two directly compressible excipients with different deformation mechanisms were compared. Avicel®PH102 (microcrystalline cellulose (MCC), FMC) undergoes plastic and elastic deformation during the compression process. Anhydrous lactose (Sheffield) fragments and the newly formed particles deform plastically and elastically during volume reduction. The excipients were lubricated at a 1% lubricant level using magnesium stearate (Mallinckrodt) or Compritol-888®(glyceryl behenate, Gattefosse). Each excipient was blended with the lubricant in a Patterson-Kelly Twin Shell Blender for five minutes. The true density of the material was measured using a Helium micropycnometer (Quantachrome).

## METHODS

### Instrumented Single Punch Tablet Press

Piezoelectric transducers were used to monitor the upper and lower punch pressures. The upper punch movement was measured with a linear variable differential transformer (LVDT). Using the upper punch LVDT, the position of the lower punch in the die was measured using a stainless steel metal tablet and a blank die.

The lubricated excipients were compressed at the same compression cycle. A series of compression cycles with different maximum punch strokes were evaluated. The speed of the press was constant at 67 tablets per minute. A standard steel 7/16" flat faced tooling set was used. Tablet weight, thickness, diameter, and hardness were measured after ejection. Three tablet computer profiles at each punch stroke were collected.

### Data Acquisition and Conversion

Three analog signals were acquired by a 12-bit, 150 KHz analog to digital converter card installed in a Beltron AT computer system. Unkelscope®data acquisition software was used to collect and store the data in binary format on a harddrive. The sampling rate per channel was one point every 0.5 millisecond in a 1.02 second event or 2048 points per channel. The binary data were converted into an ASCII or a text file using conversion routines written in Microsoft QuickBASIC® language.

**Data Analysis: Powder Densification**

QuickBASIC® programs were written to convert the upper punch movement data into powder densification (Figure 1). The transducer data were adjusted to an average initial upper baseline. The Young's Modulus of elasticity for stainless steel was used to calculate the tooling set distortion at a given pressure. An apparent fill volume was determined using the blank die and the metal tablet. The upper punch movement in the die was calculated based on the blank die position. A tablet height during compression was calculated using the upper and lower punch positions. Based on the tablet weight and true density of the powder, an apparent tablet density, tablet porosity, tablet (1 / porosity), and tablet ln (1 / porosity) were calculated for each punch movement. A corresponding upper punch and lower punch pressure describes each punch movement in the die.

Heckel Plots (ln (1 / porosity) versus upper punch pressure) representing the densification in the die were generated for each tablet formation. The densification plots have six regions which can be isolated based on the upper punch movement in the die represented in Figure 2. The in die Heckel plots for the four materials have different shapes and magnitudes of densification with pressures (Figure 5). The deformation behavior of the material is evident in each region of the plot.

A series of plots for one material can be generated for each maximum punch stroke which corresponds to the hardness range of <1.0 Kp to >20 Kp. Compacts of the lubricated excipients could be formed at constant hardness (Figure 3) or at constant thickness (Figure 4). Figures 3 and 4 represent the stress versus strain relationship of the compression cycle. The area under the curve of the force-displacement plot has been used to estimate the total work of compaction (1). The areas of the plot represent the work needed to overcome friction between particles, the net mechanical energy to form the tablet, and the elastic deformation energy stored in the tablet (1). The force-displacement data can be extended to include material properties to evaluate powder densification using different displacement cycles. A comparison of the four materials in the six regions for one maximum punch stroke is presented (Figure 4). It is proposed that these six regions can be separated and their descriptions are detailed.

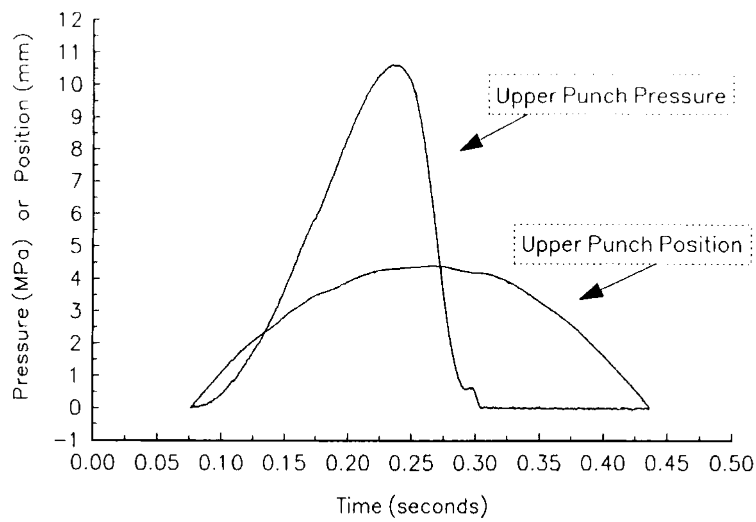


**Fig. 1.** The simultaneous collection of the upper punch pressure and the upper punch movement during the compression of Avicel PH102 lubricated with 1% magnesium stearate.

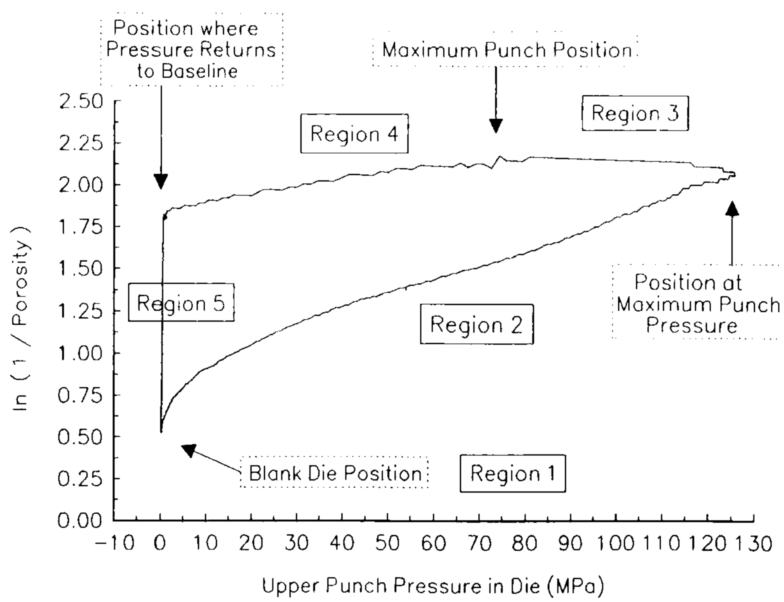


**Fig. 2.** Separation of the densification plot into six regions based on the upper punch position in the die. Region CS for Lactose, anhydrous lubricated with 1% magnesium stearate includes Regions 2, 3, 4, and 5.

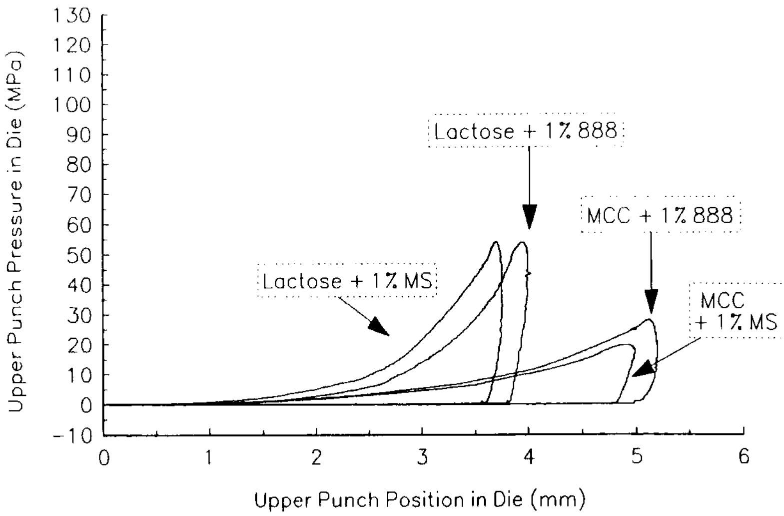


**Fig. 3.** Compression of the lubricated excipients to a tablet hardness of 5 Kp using different maximum punch strokes. **MS** = magnesium stearate **888** = glyceryl behenate **MCC** = microcrystalline cellulose

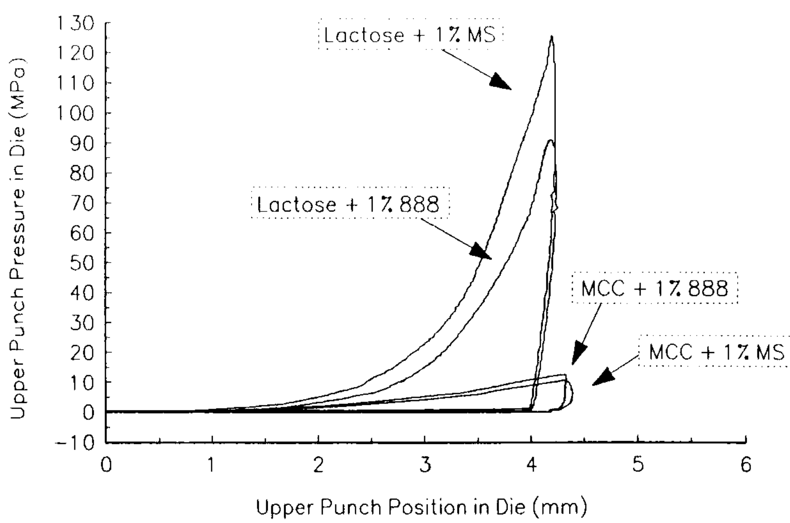


**Fig. 4.** Compression of the lubricated excipients to the same tablet thickness (3.8 mm) or to the same maximum punch stroke.

**Isolation of the Densification Regions**

**Region 1: Fill Densification**

Region 1 begins once the upper punch penetrates the die or reaches the blank die position. The region ends once the upper punch transducer senses a load. The initial fill densification achieved describes the ability of the material to flow from the hopper into the constant fill volume. The densification is related to the bulk density of the material or the flowability and the geometry of the particles. As the upper punch enters the die and makes contact with the powder bed, particles begin to rearrange. A densification is reached at which the transducer senses the applied load.

**Region 2: Compression Phase I**

Region 2 begins once the upper punch pressure is greater than the baseline of the transducer. The region ends at the maximum upper punch pressure position. As the load is applied to the material, the particles rearrange and yield to deform or fracture. If a particle fractures, the newly formed particles can deform elastically or plastically or further fracture. The shape and magnitude of the densification with pressure is indicative of the different deformation behaviors of materials. When the elastic limit of the material is exceeded, plastic or permanent deformation occurs. The resistance to densification and a corresponding increase in pressure describes a hard, brittle material resisting compression and fracture occurring in the die. Brittle materials are characterized by sudden failure with small to no plastic deformation (16). If densification increases more than the pressure, the material is easily compressed and is a soft material undergoing plastic deformation. Ductile materials are characterized by their ability to sustain very large deformations prior to final rupture (16).

**Region 3: Compression Phase II**

Region 3 begins after the maximum upper punch pressure is achieved. The region ends at the position of maximum upper punch penetration. The load of the punch is still being applied to the material at this portion of the cycle. The pressures are reducing and stress relaxation occurs within the material. The change in densification to change in pressure in the region is indicative of the viscoelastic behavior of a material. A material with viscoelasticity or time dependent behavior has elastic recovery with plastic deformation (16). It reacts immediately to loading in an elastic way then slowly deforms at some load level if maintained (16). A hard material resists further densification or has a small change in densification to pressure. Ductile materials redistribute localized stresses and have a large change in densification to pressure.

**Region 4: Decompression Phase I**

Region 4 starts from the position of maximum upper punch penetration in the die. The region ends at the position the upper punch pressure returns to the baseline of the transducer. This region describes the decompression phase of the cycle. The load or the upper punch is moving away from the compressed powder bed and out towards the die. The upper transducer senses pressure until the punch is away from the tablet surface. The elastic recovery of a material can be described by the increase in tablet porosity and the pressure changes in region 4 and 5. An elastic material has a gradual reduction in pressure and densification. A tablet height is reached where the pressure may become erratic against the punch face.

**Region 5: Decompression Phase II**

Region 5 begins when the upper punch pressure returns to the baseline of the transducer. This region continues until the upper punch reaches the blank die position or exits the die. This region describes the punch movement and pressure as the upper punch moves away from the tablet surface. The upper punch pressures are small and erratic and may correlate to further elastic recovery of the material.

**Region CS: Constant Strain**

Region CS is the area of constant punch movement or constant strain during the compression cycle. This region is defined here as the areas of at least five consecutive punch movements or densification values. Depending on the material, the area of constant strain can include the compression phase and the decompression phase regions. An area of constant strain indicates the material is resisting further densification.

## RESULTS AND DISCUSSION

The deformation behavior of the excipients and the lubricant types are not easily distinguished when comparing an entire cycle of densification (Figure 5). By separating the densification plot into regions based on the punch displacement, time dependent behavior can be studied. When the densification regions are separated into data files, deformation behavior occurring at different punch penetrations can be quantitated and compared.

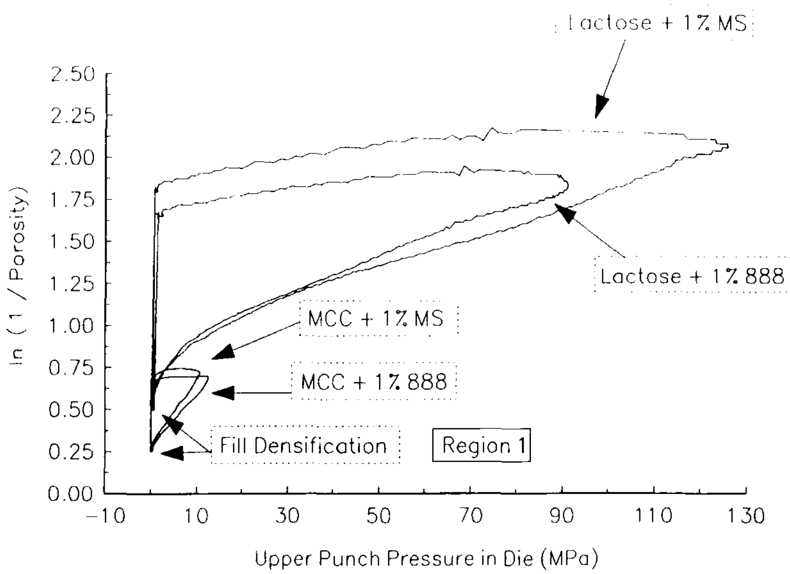


**Fig. 5.** The densification vs. the upper punch pressure during compression to the same maximum punch stroke (see Fig. 4). Region 1 is the fill densification achieved by the material.

The shape and the magnitude of the densification with pressure occurring in the six regions are different for the lubricated excipients. The changes in densification with pressure in the compression and decompression phases can be used to interpret the deformation behavior of materials.

## Region 1: Fill Densification

Region 1 describes the initial fill densification of the material in the constant fill volume (Figure 5). Table I lists the bulk density, the true density, the constant fill volume, the average tablet weight, the initial fill density, and the initial fill porosity achieved by the four materials. A fill volume of 0.75 $cm^3$ has been used for the study. The value of the initial fill density is comparable to the bulk density of the material. The initial fill density for the lactose formulations are twice that of the microcrystalline cellulose formulations. The lactose formulations achieved twice the weight in the fill volume. The bulk density, the fill density, and the tablet weight are similar for the excipients with different lubricant types.

The initial fill densification (ln (1 / porosity)) is related to the flowability of the material and the incorporation of air between the particles. The initial porosity in the fill volume is listed in Table I and ranges from 60 to 78% for the materials. The lactose formulations incorporate less air and greater material density in the volume than the microcrystalline cellulose formulations. In Figure 5, the initial fill densification for the lactose formulations is greater than the microcrystalline cellulose formulations. As the upper punch makes contact with the powder bed, the particles rearrange and the transducer senses the applied load.

**Region 2: Compression Phase I**

Figure 6 describes the densification and pressure in region 2 or the first compression phase of the cycle. The shape and magnitude of the densification and pressure are different for the materials. There is a initial region where there is a proportional change in densification with pressure. A point is reached where the densification and pressure cease to be proportional. The elastic limit of the material is exceeded and the particles yield to deform or fracture depending on the imperfections within the crystalline structure. The two points where the stress and strain are proportional to when there is no longer linearity nearly coincide for ductile materials but will vary for a brittle material (16). The densification increases with increasing pressure until a maximum pressure is reached. The inverse slope of this region has been used to describe the yield pressure of a material or the stress limit at which significant permanent deformation occurs (4, 5). A material predominately undergoing plastic deformation has a low yield pressure. A hard, brittle material requires greater pressures to yield and has a tendency to fracture during compression. The fracture propensity of a material can be described by the difference between the initial fill densification and the densification in the yielding region (4, 5). This phase is a 160 millisecond event in the compression cycle for all the materials.

The lactose formulations achieve greater pressures and densification than the microcrystalline cellulose formulations. There is an initial linear region and a point at which the elastic limit of the material is exceeded. The densification increases more than the pressure forming a curvilinear region. This may correspond to particle fracture and rearrangement in the die. The shape of the region develops in a stepwise fashion or areas where the densification is constant. The material is resisting densification and a corresponding increase in pressure occurs. The lactose formulations have low slopes or require larger pressures to yield. Lactose lubricated with magnesium stearate has an 18% higher yield pressure than the Compritol® lubricated

Table I

Parameters describing Region 1 or the initial fill densification for the lubricated excipients.

| Materials | Bulk Density ($g/cm^3$) | True Density ($g/cm^3$) | Average Tablet Weight (g) | Initial Fill Volume ($cm^3$) | Initial Fill Density ($g/cm^3$) | Initial Fill Porosity (%) |
|---|---|---|---|---|---|---|
| MCC + 1% MS | 0.344 | 1.547 | 0.2623 | 0.7505 | 0.3495 | 77.4 |
| MCC + 1% 888 | 0.344 | 1.552 | 0.2567 | 0.7519 | 0.3414 | 78.0 |
| Lactose + 1% MS | 0.641 | 1.562 | 0.4749 | 0.7503 | 0.6329 | 59.5 |
| Lactose + 1% 888 | 0.625 | 1.561 | 0.4667 | 0.7512 | 0.6212 | 60.2 |

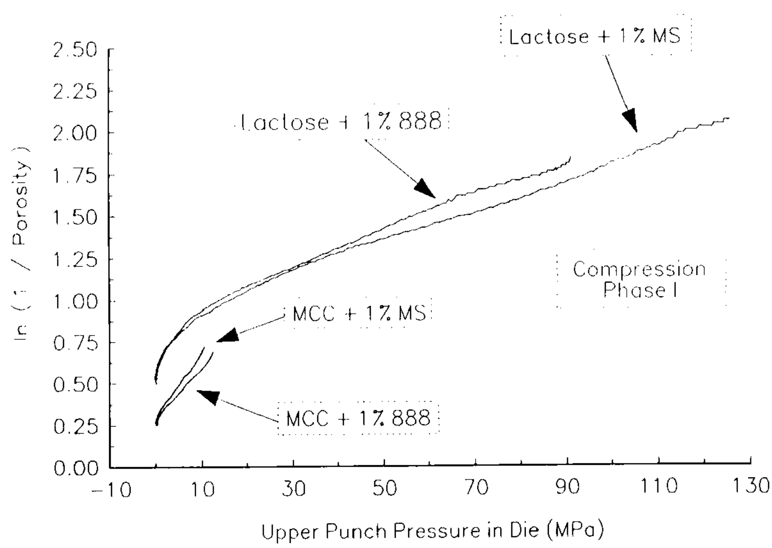


**Fig. 6.** Region 2 or the first phase of compression in the densification vs. upper punch pressure plot.

material. The lactose materials have two to three times higher yield pressures than the microcrystalline cellulose formulations. The lactose formulations have similar fracture propensities but are six to eight times greater than the propensity for the microcrystalline cellulose formulations to fracture. This behavior indicates the lactose formulations are hard, brittle materials resisting compression and fracture in the die.

The plots of the microcrystalline cellulose formulations are jagged in shape or have areas where the densification increases more than the pressure. After an initial linear region, the elastic limit of the material is exceeded. A curvilinear area forms where the densification does not increase in proportion to the pressure. This may correspond to particle fracture and rearrangement in the die. The densification increases more than the pressure as described by the steeper slopes. The microcrystalline cellulose formulations require low pressures to yield. Microcrystalline cellulose lubricated with Compritol® has a 20% higher yield pressure than the magnesium stearate formulation. The magnesium stearate formulation has a 23% larger fracture propensity than microcrystalline cellulose lubricated with Compritol®. The microcrystalline cellulose formulations require lower yield pressures to deform and undergo less particle fragmentation than the lactose formulations. The microcrystalline cellulose formulations are easily compressed and are softer materials undergoing plastic deformation.

Particle fracture creates new clean surfaces and promotes particle bonding (1). A lubricated excipient undergoing predominately plastic deformation will be sensitive to lubrication since the lubricant particles are dispersed on the surface of the particle interfering with excipient bonding. A lubricated excipient which fractures is less sensitive to lubrication because the fractured particles have increased the available surface for bonding and are clean surfaces. Microcrystalline cellulose lubricated with magnesium stearate forms a tablet having a hardness of 2.2 Kp, whereas microcrystalline cellulose lubricated with Compritol® does not have a measurable tablet hardness. The magnesium stearate formulation shows a larger propensity to fracture than microcrystalline cellulose lubricated with Compritol®. The microcrystalline cellulose formulations predominately deform plastically and are more sensitive to lubrication in terms of the effect on tablet strength. Lactose lubricated with magnesium stearate formed harder tablets (11.5 Kp) than the Compritol® formulation (7.9 Kp). The lactose formulations have higher fracture propensities and is reflected in the strength of the tablet. The relationship between the yield pressure and the fracture propensity of a material to its tablet strength is evident when comparing a series of compression cycles.

**Region 3: Compression Phase II**

Figure 7 describes densification region 3 or the second phase of the compression cycle. As the load continues to be applied, the material further densifies but the transducers sense a reduction in pressure from the material. Figure 4 illustrates that the upper punch pressure is reached before the maximum upper punch movement of the cycle. The maximum punch stroke for the compression cycle is similar for the materials at 4.2 to 4.4 millimeters in the die. The materials achieve similar tablet thickness (3.3 to 3.5 millimeters) at this maximum punch stroke. Region 3 is a rapid event covering 15 to 25 milliseconds of the compression cycle. In this region, the materials differ in the time of the region, the amount of pressure reduction, and the degree of further densification. Viscoelasticity or time dependent behavior of a material would be evident in this region. The pressures are reducing and stress relaxation occurs within the material.

When a material exerts a maximum stress against the punch face it has reached a densification at which the crystalline structure of the particles can maximally withstand the applied load. The mechanics of the press is to continue the punch movement to a set distance. The internal crystalline structure must give in terms of a rearrangement of slip planes or the material must flow under the continued applied stress. If fracture occurs then an increase in pressure would be seen but this is not observed in this region. The tendency for a material to undergo viscoelastic behavior or plastic flow can be described by the ratio of the change in densification to the change in pressure in Region 3. The time event for further densification is the ratio of the change in time to the change in densification occurring in this region. These parameters can be used to describe material differences in this phase of the compression cycle. If the time event for further densification is short and the material achieves less densification to pressure reduction, the material does not have a tendency for viscoelastic behavior. A hard material will resist further densification under the continued load. If the time event for further densification is long and the material achieves more densification to pressure reduction, the material has a greater tendency for viscoelastic behavior. A viscoelastic material will flow and further densify under the continued load. A totally elastic material has no time event because it reaches it maximum densification at its maximum pressure position (14).

The plots of the lactose formulations continue their stepwise shape, resisting further densification in the die. The time event for further densification is shorter and less densification to pressure reduction is achieved by the lactose materials. This behavior would be indicative of a hard material

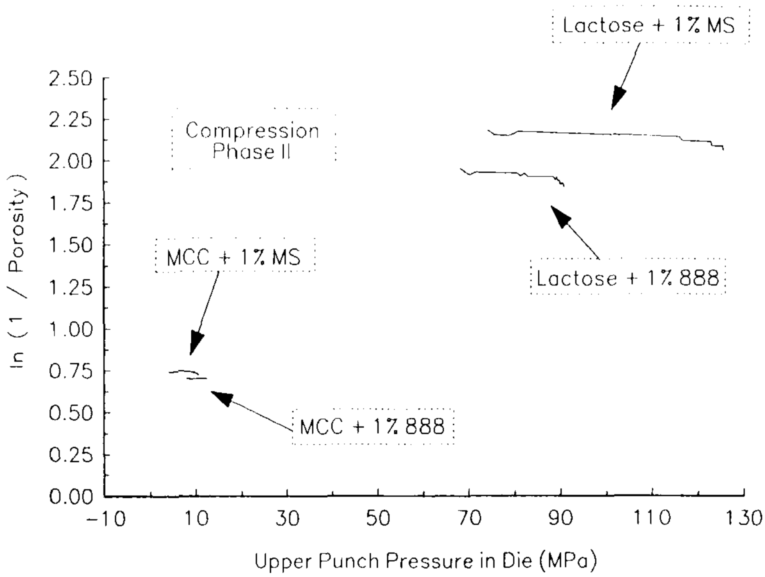


**Fig. 7.** Region 3 or the second phase of compression in the densification vs. upper punch pressure plot.



resisting further densification under the continued load. Lactose lubricated with magnesium stearate achieves 31% more densification to pressure reduction than the Compritol® lubricated material. The time event for further densification is 35% shorter for lactose lubricated with magnesium stearate than the Compritol® lubricated material. Since lactose lubricated with magnesium stearate achieves more densification to pressure reduction in a shorter time event, the further densification is not time dependent and may be due to an elastic component for the material.

The microcrystalline cellulose formulations achieve 40 to 65% greater densification to pressure reduction and have a 67 to 80% longer time event for further densification than the lactose formulations. Localized stresses are being redistributed by the ductile materials. The microcrystalline cellulose formulations have a greater tendency to undergo viscoelastic behavior in Region 3 than the lactose materials. Microcrystalline cellulose lubricated with Compritol® achieves 17% more densification to pressure reduction than the magnesium stearate lubricated material. The time event for further densification is similar for the microcrystalline cellulose materials. Microcrystalline cellulose lubricated with Compritol® has a greater tendency to undergo viscoelastic behavior than the magnesium stearate lubricated material.

**Region 4: Decompression Phase I**

Figure 8 describes densification region 4 or the first phase of decompression in the cycle. A totally elastic material will have identical compression and decompression phases on the densification-pressure plot (14). Upon load release, a totally elastic deforming material will return to its initial volume. As the upper punch face moves away from the compressed powder, the material will expand in volume proportional to the punch movement. When the applied stress is removed, the pressure exerted by the material onto the punch face is reduced. The change in densification upon pressure reduction will depend on the elastic component of a material's deformation. An inelastic material will maintain its maximum densification or porosity as the load is removed. An elastic material will expand its porosity or reduce its densification as the load is removed. The slope of this densification-pressure region can be used to describe the elastic component of a material's deformation. The larger the change in densification or the larger increase in material porosity, the steeper the slope of Region 4. Before the punch face is away from the tablet surface, the pressure may become erratic as the material undergoes elastic recovery.

The total elastic recovery of a material depends on the time at which tablet thickness is measured. The time event of this region is variable for the materials ranging from 48 to 85 milliseconds. The in die elastic recovery is defined as the tablet thickness at maximum punch penetration to the tablet thickness when the transducer returns to baseline. The out of die elastic recovery is calculated from the tablet thickness at maximum punch penetration to the ejected tablet thickness.

The lactose materials continue in a stepwise reduction in pressure and densification. Lactose lubricated with Compritol® has a 32% higher slope and a 2% higher in die elastic recovery than the magnesium stearate lubricated material. Both lubricant types have comparable in die to out of die elastic recoveries. The lactose formulations predominately undergo elastic recovery while in the die.

In the microcrystalline cellulose plots, the reduction in pressure and densification is gradual. Microcrystalline cellulose lubricated with magnesium stearate has a 49% higher slope and a 0.8% higher in die elastic recovery than the Compritol® lubricated material. Both lubricant types have a 9% increase in elastic recovery out of die versus the in die recovery. The microcrystalline cellulose formulations predominately undergo elastic recovery out of the die.

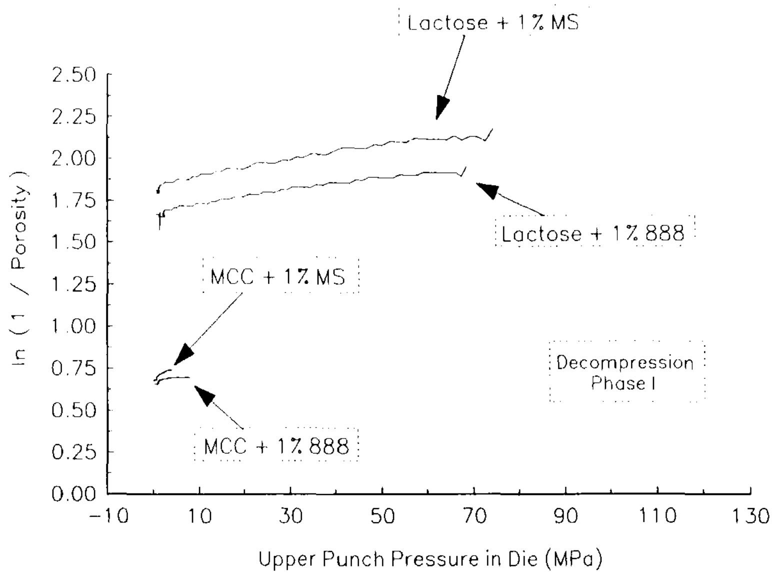


**Fig. 8.** Region 4 or the first phase of decompression in the densification vs. upper punch pressure plot.

The four lubricated materials have similar in die elastic recovery ranging from 5 to 7%. Microcrystalline cellulose lubricated with magnesium stearate has a 60% higher slope than the lactose lubricated material. Lactose lubricated with Compritol®has a 12% higher slope than the microcrystalline cellulose lubricated material. The microcrystalline cellulose materials have twice the elastic recovery out of die compared to the lactose formulations. The microcrystalline cellulose formulations have a larger elastic component to their total deformation than the lactose formulations.

**Region 5: Decompression Phase II**

Figure 9 describes densification region 5 or the second phase of decompression in the cycle. The punch is away from the surface of the tablet in this region. The pressures are small and erratic and may correspond to further elastic recovery of the material. The slopes of the densification-pressure plot are in reverse order of the slopes in Region 4. The upper punch pressure for microcrystalline cellulose lubricated with magnesium stearate immediately returns to the transducer baseline. In Region 4, this material had the largest change in densification or porosity upon pressure reduction. Lactose lubricated

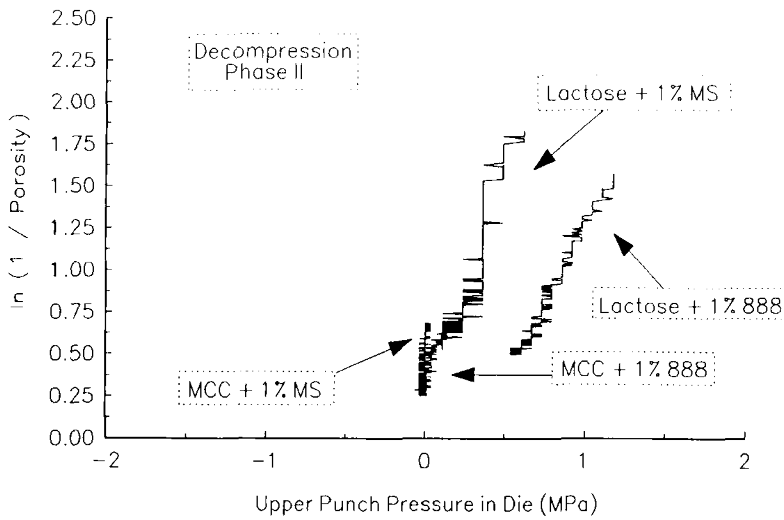


**Fig. 9.** Region 5 or the second phase of decompression in the densification vs. upper punch pressure plot.

with magnesium stearate has the largest slope in Region 5. This material had the smallest densification change with pressure reduction in Region 4. Lactose lubricated with magnesium stearate has a 25% higher slope than the microcrystalline cellulose lubricated with Compritol®. Microcrystalline cellulose lubricated with Compritol®has a 32% higher slope than the lactose lubricated material.

## Region CS: Constant Strain

Figure 10 describes densification region CS or the area of constant strain. An area of constant strain indicates a material is resisting further densification during the displacement cycle. The constant strain area for the four lubricated excipients includes the compression and decompression phases of the cycle. The two excipients differ in the time point the strain occurs in the regions of the cycle. The time duration for the resistance to densification is different between the excipients. The time duration of this region for the lubricant types are similar for each excipient. The resistance to densification in the regions can be explained by the different deformation behaviors of the materials.

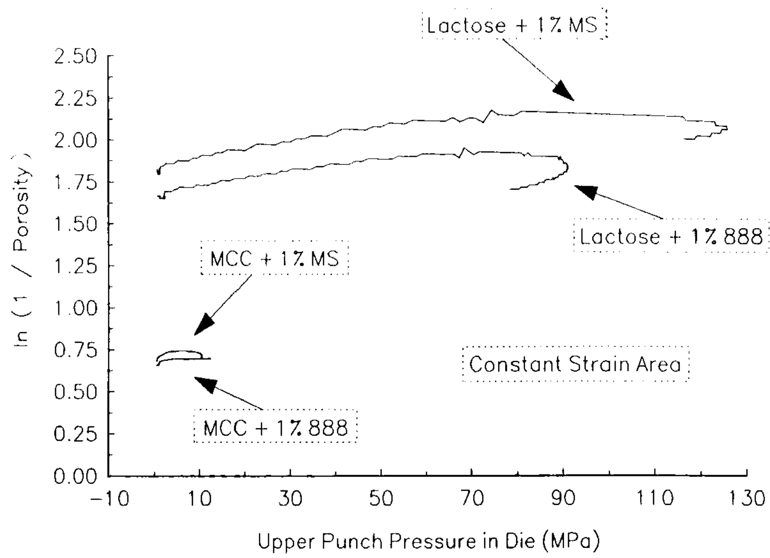


**Fig. 10.** Region CS or the area of constant strain in the densification vs. upper punch pressure plot.

Lactose lubricated with Compritol® resists further densification in Region 2, 3, and 4. The other lubricated excipients resist further densification in Region 2, 3, 4, and 5. The lactose formulations resist further densification in a 19 to 23% longer time period than the microcrystalline cellulose formulations. The lactose formulations resist densification at an earlier time point in Region 2 than the microcrystalline cellulose formulations. This is explained from the higher fracture propensity of the lactose formulations during compression. In Region 3, the lactose formulations have less of a tendency for viscoelastic behavior and undergo less further densification than the microcrystalline cellulose formulations. The lactose formulations undergo constant strain at later time points in Region 4 and 5 compared to the microcrystalline cellulose formulations. This is explained from the smaller elastic recovery or the smaller change in densification or porosity for the lactose formulations.

## CONCLUSIONS

The ability of a material to deform elastically, plastically, to fracture, and to undergo plastic flow during the compression process can be monitored by an instrumented single punch tablet press. The measurement of material densification with pressure in the die describes the deformation process to form the tablet. The Heckel densification-pressure plot has six regions which can be isolated based on the upper punch movement in the die. By separating the plot in terms of punch displacement positions, the deformation stages of a material can be studied. The six regions are the fill densification, the first and second phases of compression, the first and second phases of decompression, and the area of constant strain. The shape and magnitude of the densification with pressure in the six regions can be used to interpret the deformation behavior of a material. The lubricant type and the excipients have characteristic deformation behavior in the phases of the cycle. The Heckel method can differentiate the effects of lubricant type on the deformation process.



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