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ORIGINAL ARTICLE

Detrimental consequences of the Paracetamol tablet elastic relaxation during ejection

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Abstract

Background: It is generally accepted that the tablet elastic relaxation during compaction plays a vital role in undermining the final tablet mechanical integrity. One of the least investigated stages of the compaction process is the ejection stage. *Method*: This work has successfully monitored the paracetamol tablet dimensional changes during ejection using noncontact dimensional measuring devices. The extent of the tablet damage was physically viewed by examining the presence of cracks on the tablet side surfaces upon complete ejection from the die cavity. *Results*: Damaged tablets were obtained when the paracetamol tablets exhibited comparatively high elastic relaxation during the ejection stage of the compaction process. *Conclusion*: Hence, this work presents evidences of the detrimental consequences of the paracetamol tablet elastic relaxation during ejection on its final mechanical integrity..

Key words: *Capping; compaction; ejection; elastic relaxation; lamination; stored elastic energy*

Introduction

The damage of tablets by capping and lamination when they are ejected from the die after the compaction process will invariably lead to production failure. Capping is a physical situation whereby a portion of the tablet body is detached from its main body. Complete detachments can occur when the tablet emerges from the die cavity or in some cases, the upper part of the ejected tablet body can be easily removed by hand[1]. Meanwhile, lamination is a term describing the situation when the tablet breaks into several horizontal thin layers across its diameter. The internal crack in the tablet that causes capping and lamination is believed to propagate axisymmetrically from the periphery of the tablet upper radial surface adjacent to the moving upper punch to the center of the tablet[2].

Early works considered the entrapment of air in the powder bed during the application of load that causes capping[3]. It is suggested that the entrapped air would accentuate the separation of the tablet body when internal faults existed in it during the unloading stage. However, another research conducted showed that capping and lamination were also present for tablets formed in vacuumed dies[4]. Decreasing the amount of air present has been found to reduce the capping tendency of the tablets, but increases the tablet lamination tendencies[5]. Hence, the presence of air is not the sole cause for the capping and lamination of tablets.

Some workers considered that capping occurred at the end of the loading stage[6] because of the elastic relaxation. They measured the radial die wall stresses and observed that after the unloading stages for capped tablets they were relatively lower than those for coherent tablets. Sugimori and Mori[7] further suggested that the low residual radial die wall stresses after the unloading stage is the result of the capping of the tablet during the decompression phase, and not the cause of capping. They arrived at this conclusion by observing the existence of relatively high radial die wall stresses at the final stages of the unloading, which decayed immediately to low values upon complete unloading.

During the unloading of the applied stress, the elastic relaxation of the tablet depicted by its height expansion will create relatively lower stress regions in the upper part of the tablet compared with that in the bottom half[2]. Localized, intensive shear stresses have been shown to

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exist in the tablets prone to capping after the unloading stage, which corresponds to the crack patterns in a capped tablet by using a computer simulation based on the finite element method (FEM) modeling[2,8]. Hence, the researchers attributed this as the cause of capping during the unloading stage.

An inhomogeneous density distribution of the materials within the tablet because of the influence of the die wall friction during compaction has also been attributed to the capping of tablets[9,10]. A stress gradient is thought to occur[11] in the regions between the still constrained and unconstrained tablet body that would then lead to capping and lamination of the tablets during emergence.

Recently, it has been suggested that most probably capping and lamination occurred or is further accentuated during ejection[12] although no experimental evidence have been put forward in the literature. Even though a number of researches have dealt on the origins of capping and lamination as discussed in the preceding paragraphs, the role of the ejection stage has not been experimentally studied in detail. Hence, this article aims to elucidate the crucial role of the elastic relaxation in the ejection stage of the compaction process. This was achieved by examining the elastic relaxation behavior of paracetamol tablets that are known to exhibit capping and lamination tendencies[13] by use of a novel tablet dimensional measurement apparatus published recently[14].

Materials and methods

Material and tablet formation

Damaged paracetamol tablets were produced by means of enhancing the capping and lamination tendencies through the optimization of the compaction conditions. A universal testing machine (Lloyds Instruments, Bognor Regis, UK) with a 50-kN load cell was used in the formation of the tablets in a 12.94-mm diameter stainless steel die (Specac, Kent, UK). Figure 1 shows the compaction cycles employed in this work. To produce damaged tablets, paracetamol tablets having masses of 1.2 g each were formed in an unlubricated die system. Figure 2 shows the scanning electron microscopy (SEM) photograph of the paracetamol powders used in this work (Sigma-Aldrich, Munich, Germany). The compaction velocities during the loading and unloading stages were maintained at 4167 μm/s. The powders were compacted to form tablets at several compaction stresses, which are 29, 95, 179, and 341 MPa, respectively.

Ejection

General preparation

Before starting the ejection experiment, the bottom punch was removed and the 50-kN load cell was programmed into intimate contact with the upper punch.

Tablet height elastic relaxation

The apparatus described previously[14] was utilized in the measurement of the tablet height changes during the ejection stage. The displacement of the tablet bottom surface was measured through the use of a laser displacement sensor (model LG10A65PIQ, Banner Engineering, Minneapolis, MN, USA). Meanwhile, the tablet top surface displacement was measured by the displacement transducers of the testing machine. Hence, the change in the tablet height, Δy, is given by[14]

$$y_b - y_t = \Delta y \tag{1}$$

where y_b is the tablet bottom surface displacement and y_t is the tablet top surface displacement.

Tablet diametrical elastic relaxation

A laser micrometer (VG-301, Keyence Corp., Osaka, Japan) was used in the measuring and recording of the tablet diameter during its emergence from the die cavity according to the experimental procedure outlined previously[14].

Qualitative assessment of tablet damage and the ejection work

Digital photographic images of the ejected paracetamol tablets were taken to record the capping and lamination of the tablets. SEM images were also taken of the tablet side surfaces.

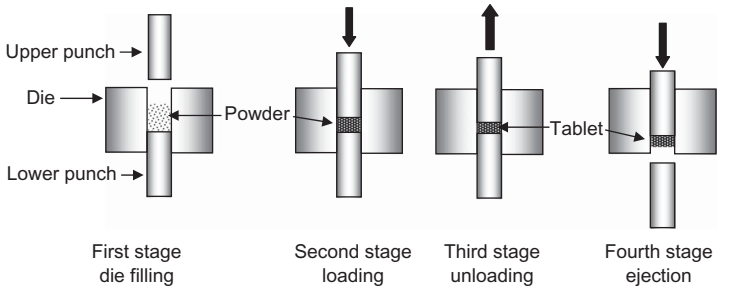

Figure 1. The uniaxial die compaction cycle utilized in this work in the formation of the paracetamol tablet.

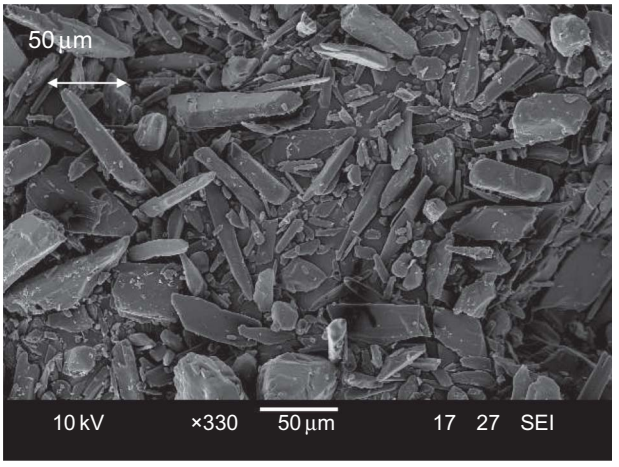

Figure 2. SEM picture of the paracetamol powder (×330).

Results and discussions

Tablet height and diametrical elastic relaxation

Tablet height elastic relaxation

The general trend of the paracetamol tablet height elastic relaxation profiles (Figures 3–6) indicates the presence of an initial height reduction, which is the tablet recompression phase represented by the negative Δy values. This is followed by the tablet height expansion, represented by the positive Δy values. The initial tablet height reduction corresponds to the phase when the ejection force increases abruptly to a maximum value and then decreases as the tablet experiences a height expansion during its subsequent movement during ejection. This is believed to be due to the dependency of the ejection force, which is the measure of the frictional resistance to the tablet movement during ejection, upon the tablet internal stored elastic energy[14]. The origin of the stored elastic energy is due to the existence of elastic strains incurred during the deformation of the particles during the loading stage[15]. The ejection force that is dependent on the tablet radial die wall stresses arises when the internal stored elastic energy causes the tablet body to elastically relax and thus push onto the die walls during ejection. When the paracetamol tablet relaxes, depicted by the increase in its height (Figures 3–6), it releases its stored elastic energy and hence the decrease in the measured ejection force. Similarly, the increase in the

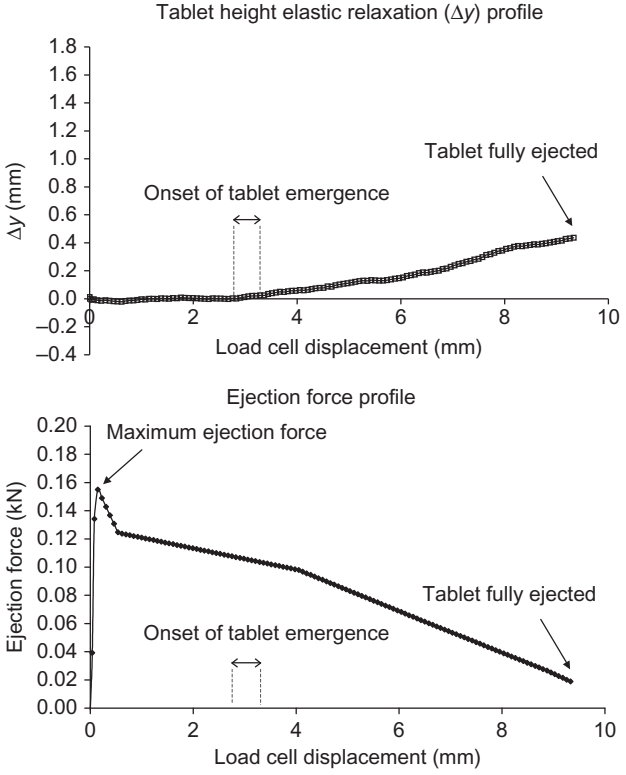

Figure 3. The paracetamol tablet height elastic relaxation (Δy) and the ejection force profiles at 29 MPa compaction stress in an unlubricated die system. The increase in the tablet height corresponds to a decrease in the ejection force.

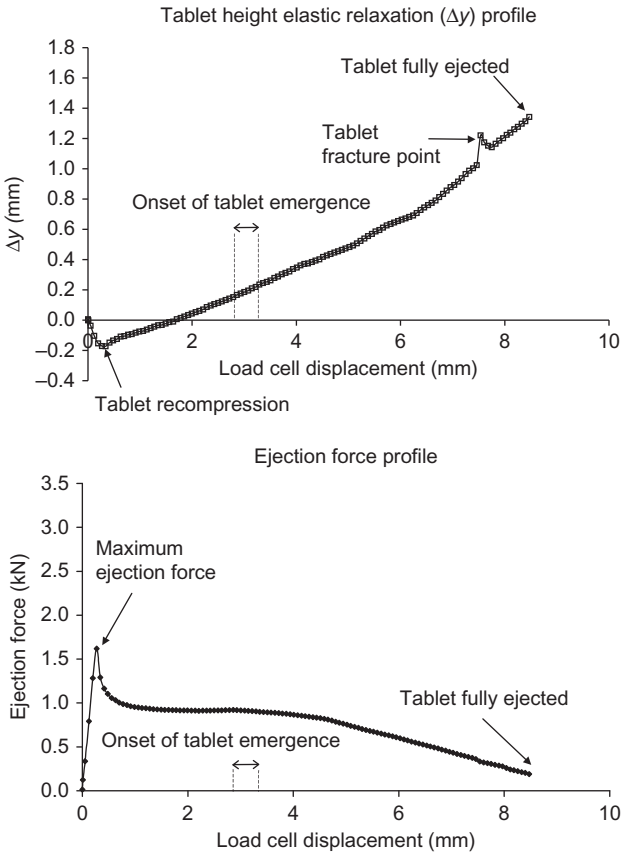

Figure 4. The paracetamol tablet height elastic relaxation (Δy) and the ejection force profiles at 95 MPa compaction stress. Note the occurrence of an abrupt elastic relaxation in the elastic relaxation profile believed to be the fracture point of the tablet during the ejection.

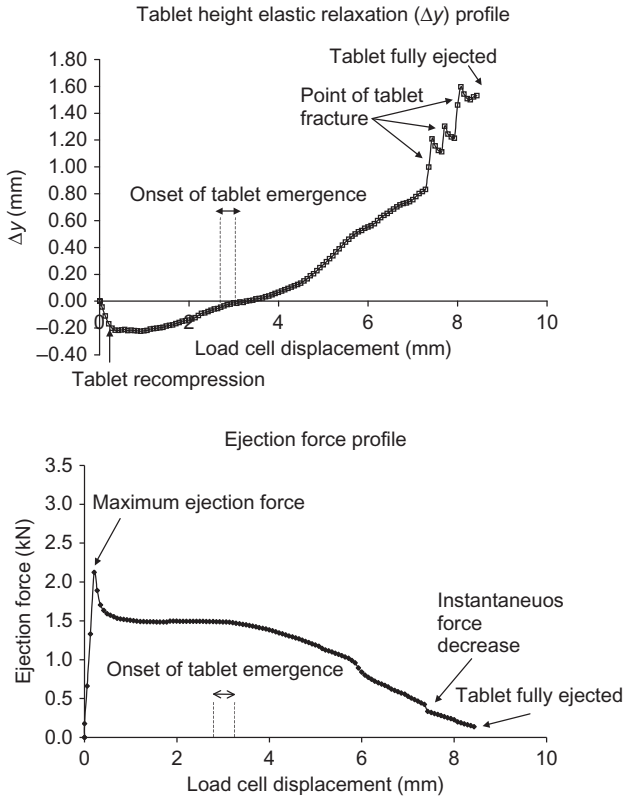

Figure 5. The paracetamol tablet height elastic relaxation (Δ*y*) and the ejection force profiles at 179 MPa compaction stress. Note the occurrence of abrupt elastic relaxations in the elastic relaxation profile, which correspond to the instantaneous decrease in the ejection force.

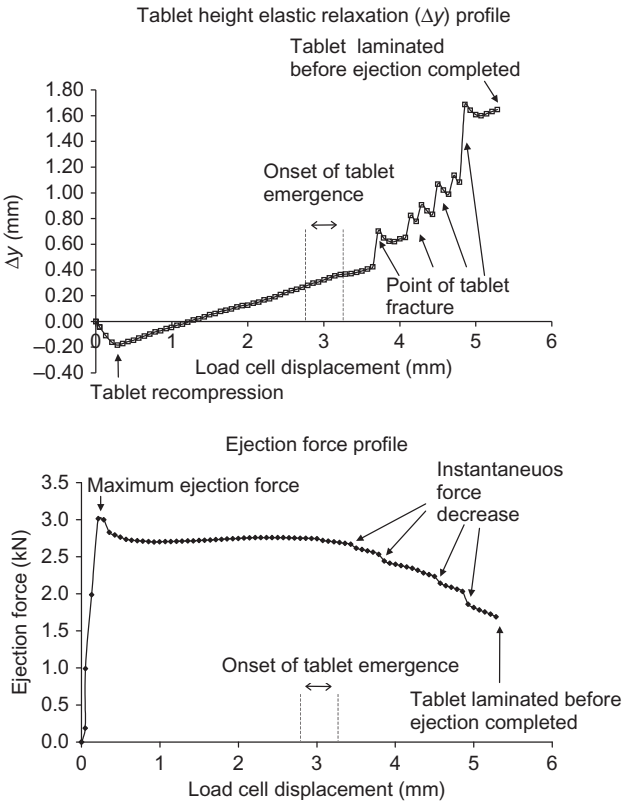

Figure 6. The paracetamol tablet height elastic relaxation (Δ*y*) and the ejection force profiles at 341 MPa compaction stress. The tablet laminated before ejection completed.

measure ejection force is due to the increase in its internal stored elastic energy when it undergoes a recompression in the initial phase of the ejection.

Another important aspect of the paracetamol tablet height elastic relaxation is the occurrence of a rapid elastic expansion followed by a contraction depicted by the abrupt increase and decrease of the Δ*y* values. This cyclic elastic relaxation behavior of the tablet is more pronounced when the compaction stress increases. It is believed that these abrupt changes in the tablet height, which occur as the tablet is nearly ejected from the die cavity, represent the sudden release of the tablet stored elastic energy because of the tablet experiencing fracture. This reasoning is further supported by the sudden drop in the measured ejection force that corresponds with the rapid elastic relaxation behavior as depicted in Figures 5 and 6. However, the probable fracture point observed in height elastic relaxation profile of the tablet formed at the lower compaction stress of 95 MPa (Figure 4) does not show any drop in its corresponding ejection force. This probably indicates that the release of the tablet stored elastic energy when the tablet fractured has a lesser effect on the die wall stresses and ultimately the ejection stress in comparison with those in the case of the higher compaction stresses of 179 and 341 MPa (Figures 5 and 6). The location of these probable fracture points at the top half of the tablet body gives an indication of the presence of a nonuniform radial die wall stress along the tablet body where it is assumed to be higher near the top half of the tablet body and decreasing toward the bottom half. Therefore, the relatively higher die wall stresses located near the upper tablet body adjacent to the moving upper punch will then be reflected in a relatively higher elastic relaxation in the region and hence the occurrence of capping and lamination in this particular section of the tablet body.

Tablet diametrical elastic relaxation

When the tablet initially emerges from the die cavity, there is a sudden increase in the tablet diameter, which then decreases to a lower value (Figures 7–10). The amplitudes of these initial diameter fluctuations are approximately between 20 and 40 μm measured between the highest and lowest recorded tablet diameter. It is assumed that the localized cyclic expansion–contraction cycles originated from the release of the localized stored elastic energy. Apart from the localized cyclic diametrical variations, the general feature of the profiles indicates that the average diameter of the tablet varies,

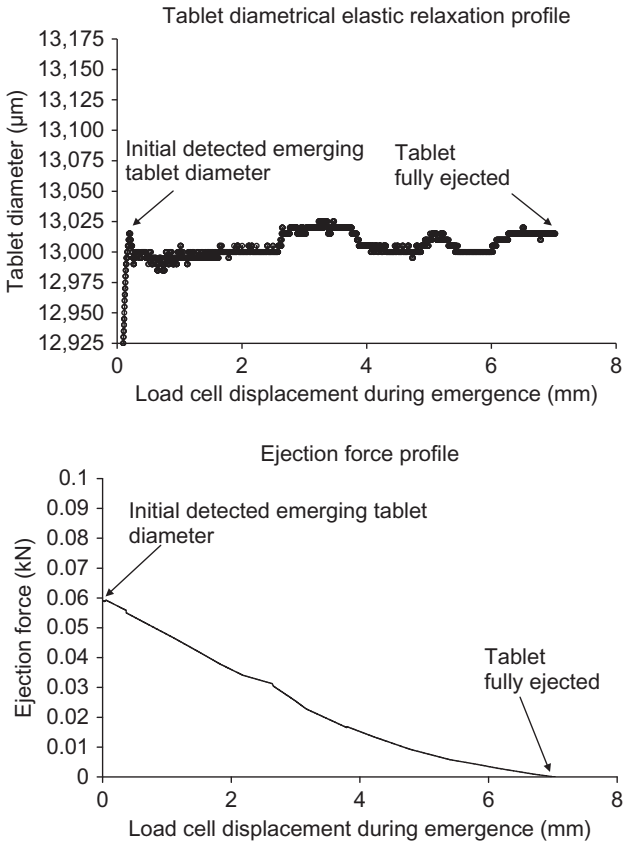

Figure 7. The paracetamol tablet diametrical elastic relaxation and the ejection force profiles at 29 MPa compaction stress. Note the waviness in the diametrical elastic profile.

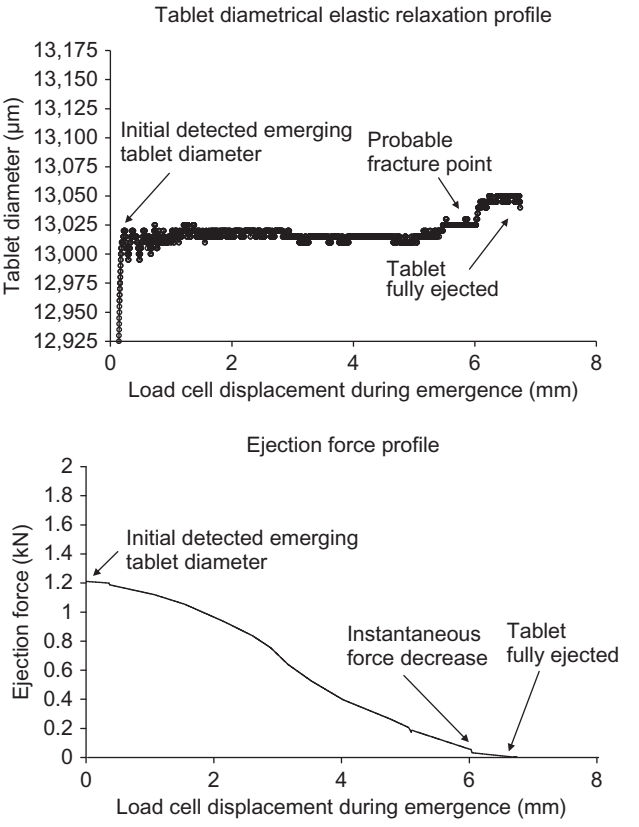

Figure 8. Tablet diametrical elastic relaxation and the ejection force profiles at 95 MPa compaction stress. Note the abrupt diametrical expansion at the top part of the tablet near the end of the ejection stage corresponding to the decrease in the ejection force, which is believed to be the fracture point of the damaged tablet.

which in most cases, as illustrated in Figures 8–10, displays a higher measured tablet diameter as it is nearly ejected from the die. This gives further evidence on the notion that for the case of the paracetamol tablets, a higher elastic relaxation, which is caused by a higher tablet internal stored elastic energy, is located in the upper region of the tablet body. The increase in the tablet diameter is also nonlinear, giving indications of a nonlinear elastic relaxation gradient present along the tablet circumferential surfaces. An examination of the ejection force profiles as shown in Figures 7–10 also supports this reasoning as the force profiles varies nonlinearly when the tablet is extruded from the die cavity.

Similar to the tablet height profiles shown earlier in Figures 3–6, the diametrical profiles also illustrate sudden localized elastic relaxations in the upper part of the tablet body. This is indicated by an abrupt increase in the tablet diameter, which corresponds to the drop in the ejection force, where this abrupt change in the tablet diameter increases with the compaction stress. The regions where these localized elastic relaxations occur are believed to be the fracture points on the tablet body.

In general, when the compaction stress increases, the final tablet diameter measured at the end of the ejection increases. The rapid elastic relaxation occurring at the end of the ejection stage that is assumed to represent the fracture point on the tablet body also increases as the applied compaction stress increases. At the low compaction stress of 29 MPa (Figure 7), there is no obvious abrupt change in the tablet diameter in the upper part of the tablet body, instead a 'waviness' in the profile is observed. It is assumed that this implies that the tablet does not suffer obvious surface cracks, which is proven by the visual inspection of the tablet. Nevertheless, the 'waviness' in the diametrical elastic relaxation profile suggests that the overall mechanical integrity of the tablet might be compromised because of the weakening of the tablet internal bonds caused by the stretching and contraction of the tablet body during emergence.

Fracture characteristic of the damaged Paracetamol tablets

As discussed earlier, the severity of the tablet damage increases with the applied compaction stress. The tablet damage is characterized in terms of the presence of

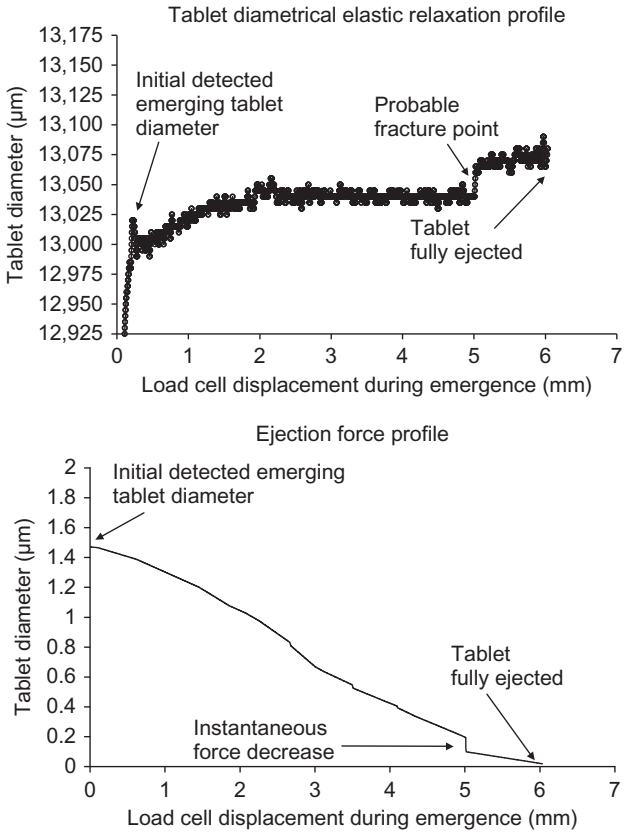

Figure 9. The paracetamol tablet diametrical elastic relaxation and the ejection force profiles at 179 MPa compaction stress.

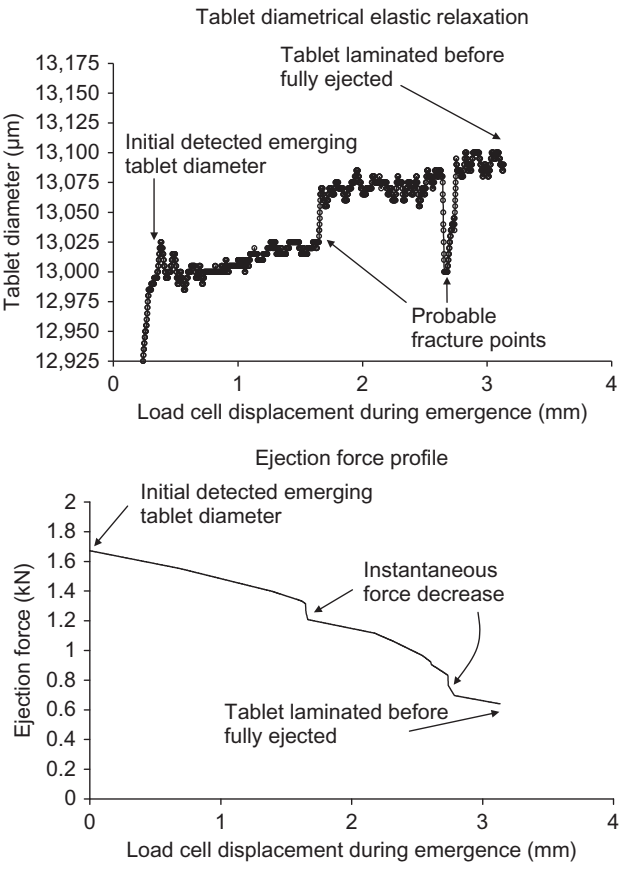

Figure 10. The paracetamol tablet diametrical elastic relaxation and the ejection force profiles at 341 MPa compaction stress.

cracks by means of direct physical observation on the tablet diametrical side surfaces. Figures 11 and 12 show the damage incurred by the paracetamol tablets upon ejection. At the lower compaction stress of 179 MPa (Figure 11), a single crack can be observed resulting in capped tablets whereas at the higher compaction stress of 341 MPa (Figure 12), several horizontal cracks appeared across the tablet diameter and will probably be more suitable to be described as a lamination failure. The region in which the cracks appeared is located in the upper part of the tablet body. It is assumed that the presence of a higher elastic relaxation in this region is caused by the additional radial die wall stresses exerted by the moving upper punch onto the area adjacent to it on the tablet body, which is the upper part of the tablet during ejection. A higher compaction stress will produce a higher tablet initial radial die wall stress before ejection, which then resulted in a higher tablet elastic relaxation during ejection. This in turn will be more detrimental toward the tablet mechanical integrity as illustrated in Figures 11 and 12.

Close examinations of the tablet side surfaces through the use of the SEM imaging demonstrate variations of the deformation characteristics of the surfaces from the top toward the bottom half of the tablet (Figures 13–15). Apart from the obvious crack formations seen earlier in Figures 11 and 12, there are more radial surface cracks that are parallel to the main crack and the tablet counterfaces as illustrated by the SEM images. The crack opening relatively decreases from the top toward the bottom half of the tablet, and no cracks are visible on the surfaces near the bottom half as shown in Figure 15. The increase in the relative crack severity depicted by the larger crack opening near the top part of the tablet implies the presence of relatively higher stresses therefore producing a higher elastic relaxation leading toward the pronounced failures. The surfaces are also smoother near the top half (Figure 13) compared with those near the bottom half (Figure 15) of the tablet where apparent individual particles can still be distinguished. These led toward the conclusion of more deformed particles at the top half of the tablet side surfaces in comparison with those located near the bottom half further supporting the notion of the presence of a high stress region in the upper half of the tablet body.

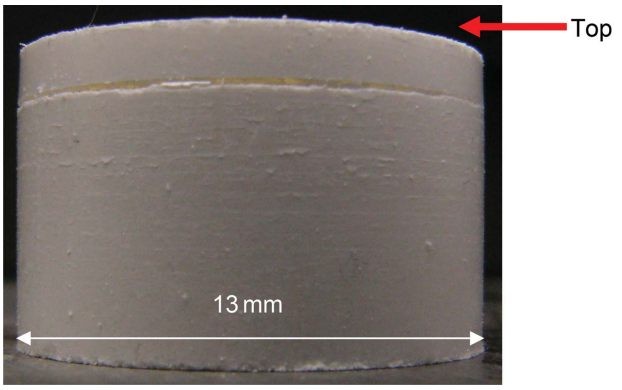

Figure 11. A 1.2-g paracetamol tablet formed at 179 MPa in an unlubricated die.

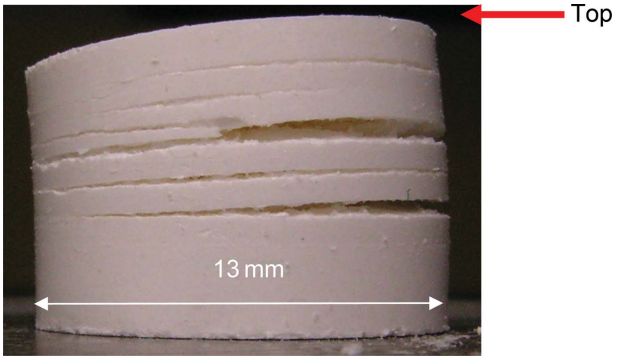

Figure 12. A 1.2-g paracetamol tablet formed at 341 MPa in an unlubricated die.

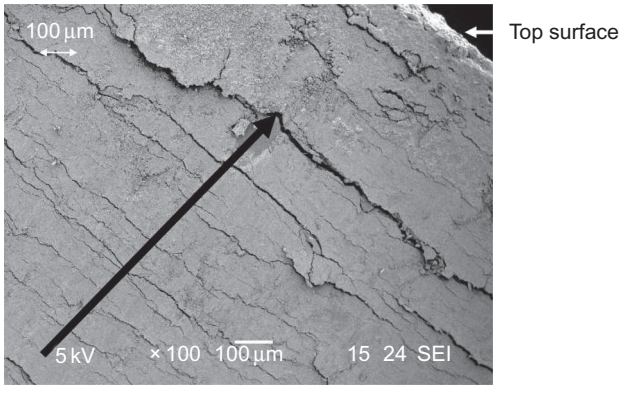

Figure 13. Side surface near the top half of an ejected 1.2 g paracetamol tablet, where the black arrow indicates the direction toward the top and the white arrow shows the top surface of the tablet (×100 magnification).

Conclusion

The severity of the paracetamol tablet damage increases when it exhibits a relatively high elastic relaxation.

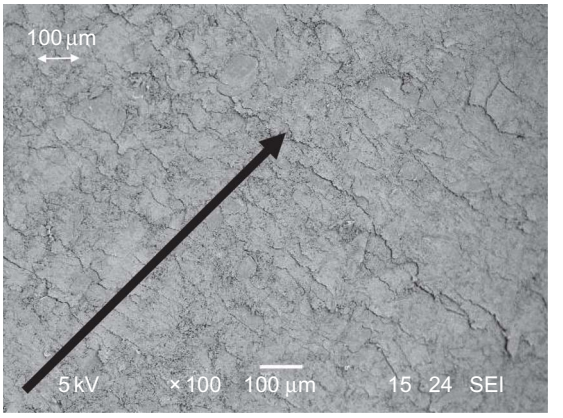

Figure 14. Side surface in the middle half of an ejected 1.2-g paracetamol tablet, where the black arrow indicates the direction toward the top half of the tablet (×100 magnification).

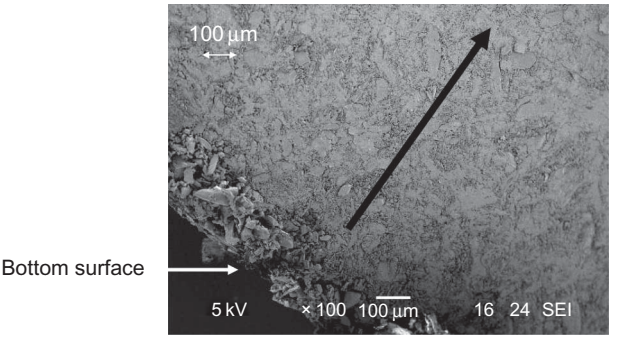

Figure 15. Side surface near the bottom half of a 1.2-g paracetamol tablet, where the black arrow indicates the direction toward the top (×100 magnification).

Hence, the paracetamol tablet releases its internal stored elastic energy in terms of its height and diametrical elastic expansion causing it to be damaged during ejection from the die cavity. Abrupt localized elastic relaxations were also observed in the upper part of the tablet body in both the tablet height and the diametrical elastic relaxation profiles, giving indications of the probable fracture points occurring in the upper region of the tablet body. These findings were then confirmed by the visual images of the damaged tablets where cracks were observed in the upper part of the tablet body. This is in contrast to the lower part where no apparent cracks were observed.

Declaration of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of this paper.

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