International Journal of Pharmaceutics, 66 (1990) 143-148
Elsevier

IJP 02257

Fracture mechanics of microcrystalline cellulose powders

P. York[1], F. Bassam[1], R.C. Rowe[2] and R.J. Roberts[2]

[1]*Pharmaceutical Technology, School of Pharmacy, University of Bradford, Bradford BD7 1DP (U.K.) and* [2]*ICI Pharmaceuticals Division, Macclesfield, Cheshire SK10 2NA (U.K.)*

(Received 2 April 1990)
(Modified version received 20 July 1990)
(Accepted 24 July 1990)

Key words: Microcrystalline cellulose powder; Fracture mechanics; Critical stress intensity factor; Notched beam specimen; Four-point beam bending

Summary

A fracture mechanics approach has been successfully applied to determine K_{IC}, the critical stress intensity factor and a measure of brittleness of materials, using notched beam specimens in four point flexure testing. Seven chemically equivalent microcrystalline cellulose samples have been examined and, based on determined values of K_{IC}, all samples have been classified as semi-brittle with respect to crack propogation and fracture mechanics. The generally minor differences found in K_{IC} values between different suppliers and grades are attributed to alternative processing conditions and variations in solid-state properties.

Introduction

Whilst considerable attention has been directed to the study of the compaction behaviour of pharmaceutical powdered solids, such characterisation has in general been constrained by techniques selected to reflect end-use of the materials. Thus in tabletting work, pressure/volume relationships obtained using instrumented presses, have been extensively measured, as have processing and particulate effects on tablet strength. Such studies give indications of the deformability of materials but assessment and quantification of the definitive mechanical constants describing brittleness (i.e., the fragmentation propensity) and ductility (i.e., the ability to deform by plastic flow) is not available.

Several recent studies have however adopted methodologies used in engineering to consider the mechanical properties and fracture mechanics of pharmaceutical powders formed into suitable specimens (Mashadi and Newton, 1987a,b, 1988; Roberts and Rowe, 1987, 1989; Bassam et al., 1988, 1989) in an attempt to probe their definitive mechanical properties. Since many pharmaceutical materials can be classified as semi-brittle or brittle (Roberts and Rowe, 1987), a fracture mechanics approach to determine K, the stress intensity factor can be applied. K describes the brittleness of materials as reflected by the resistance of a material to the propogation of a crack, by quantifying the stress field near the crack tip. The crack grows when the stress in the specimen has been raised to a critical value. K is proportional to the general stress in the material and the square

Correspondence: P. York, Pharmaceutical Technology, School of Pharmacy, University of Bradford, Bradford BD7 1DP, U.K.

root of the crack length and thus has units of MPa $m^{1/2}$.

Brittleness results from little or no plastic deformation before fracture, since no significant dislocation motion is possible in the material to allow overall plasticity.

In this study a range of chemically equivalent microcrystalline cellulose powders from different sources and of different particle sizes was examined. A four point beam bending technique was employed with notched beams over a range of beam porosities to determine K. Microcrystalline cellulose, a widely used excipient in solid dose formulations, is a polymeric, material and alternative preparation routes employed by different manufacturers could invoke changes in important properties, influencing the fracture behaviour of prepared specimens or tablets.

Materials and Methods

The materials examined were Avicel PH101, Avicel PH102, Avicel PH105 all from FMC Philadelphia, Emcocel 90M and Emcocel, both from Edward Mendell (Europe) Ltd, and Unimac MG100 and Unimac MG200 from Unitika Rayon, Japan. All samples were used as supplied and stored at 45 ± 5% R.H. and 20°C for at least 1 week prior to preparation of beam specimens. Particle sizes reported are those provided by the manufacturers. Rectangular beam specimens were prepared using a hardened steel punch and die set and a 500 kN press (Bassam et al., 1989). Since the presence of discontinuities, such as flaws and pores, in specimens can act to localise high stresses a notch (or dominant flaw) was introduced to reduce the influence of discontinuities. Notches of different profiles and dimensions were accurately cut into the upper beam surface using a cutting tool fitted into a lathe.

Notched specimen beams of known porosity, calculated from beam dimensions and weight, were then flexure tested to break using a modified CT40 mechanical tester (Engineering Systems, Nottingham) (Bassam et al., 1989). A typical force/displacement (stress/strain) curve is shown in Fig. 1. If the mode of crack surface displacement involves an opening mode due to the action of tensile stresses on the crack walls, the subscript I for K is used. This is the common mode of fracture for brittle materials since modes II and III involve shear stresses. K_{IC}, the stress intensity factor under critical (i.e., limiting) conditions at crack propagation, can be calculated from Eqn 1 (Brown and Srawley, 1969):

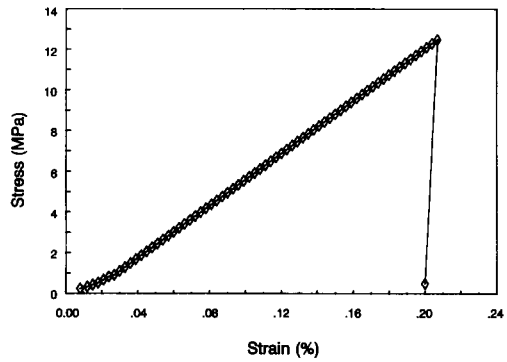

Fig. 1. Representative stress-strain plot for an Avicel PH102 notched beam.

$$K_{IC} = \frac{3P_{IC}a^{0.5}(L_1 - L_2)v}{2bh^2} \quad (1)$$

where P_{IC} represents load at failure, a is notch depth, L_1, L_2 denote inner and outer loading spans on a four-point testing rig, b is beam width, h denotes beam thickness and v is compliance, where

$$v = 1.99 - 2.47(a/h) + 12.97(a/h)^2 - 23.17(a/h)^3 + 24.80(a/h)^4 \quad (2)$$

All beam specimens were conditioned at 45 ± 5% R.H. and 20°C for 1 week prior to test unless otherwise stated.

Results and Discussion

It is well known in fracture mechanics that the data generated depend on many factors. These include the choice of test and its associated geometry, the testing conditions of loading rate and en-

vironment (humidity), the method of formation of the specimen and the degree of porosity. It is thus pertinent to discuss those factors relevant to this work.

Testing conditions

Rate of loading experiments with beams of Avicel PH101 induced a small rise (approx. 10%) in K_{IC} values for a 100-fold increase in applied loading rate (0.12 to 10.00 mm min^{-1}). This is consistent with previous work albiet on sodium chloride which showed only a 20% increase in K_{IC} values for a 3000-fold increase in loading rate (Roberts et al., 1989). Consequently all data reported here have been measured at a loading rate of 0.5 mm min^{-1}.

Since the mentioned properties of modulus and yield stress of microcrystalline cellulose powders are known to be sensitive to humidity and moisture content (Roberts and Rowe, 1988; Bassam et al., 1989) it is not surprising that K_{IC} values for Avicel PH101 specimens also depend on humidity (Table 1). It is clear that beams exposed to 75% RH by storage over saturated sodium chloride solution are less resistant to crack propogation. Similar results have been found for soda-lime glass by Wiederhorn (1967) who suggested that the effect was caused by water interacting at the crack tip.

Data for the effect of notch shape and dimension are given in Table 2 for some Avicel PH101 beams. Whilst the arrow head type notch influenced the measured value of K_{IC}, this effect was much reduced from straight through notches. A notch width and depth of 0.1 and 1.00 mm, respectively, were selected for all further work. Notch geometry is significant in that it can influence crack growth behaviour and thus affect the results compared to other methods used for the determination of K_{IC}, as will be discussed later.

TABLE 1

Effect of storage humidity on critical stress intensity factor (K_{IC}) for Avicel PH101 beams, at 20°C

Relative humidity (%)	Porosity	K_{IC} (MPa $m^{1/2}$)
45	0.14	0.46
	0.10	0.57
76	0.17	0.16
	0.13	0.18

TABLE 2

Effect of notch shape and size on critical stress intensity factor (K_{IC}) for Avicel PH101 beams, at 10% porosity

Shape of notch	Depth (mm)	Width (mm)	K_{IC} (MPa $m^{1/2}$)
Arrow-head, 90° internal angle	0.5	1.0	0.42
	1.0	2.0	0.46
	1.5	3.0	0.51
Straight-through notch	1.0	0.1	0.47
	1.0	0.6	0.50
	1.0	0.8	0.50
	1.0	1.5	0.45
	2.0	0.1	0.47
	3.0	0.1	0.48

Effect of specimen porosity

Figs 2–4 illustrate plots of K_{IC} vs porosity for the various sources of microcrystalline cellulose. As the porosity decreases, K_{IC} increases indicating that the specimen is more resistant to crack propogation at lower porosity. During the initial stages of compression, the large pores which control the strength of the specimen are removed first, followed by smaller ones. As the powder becomes more consolidated it becomes less brittle being able to absorb greater loads before failure.

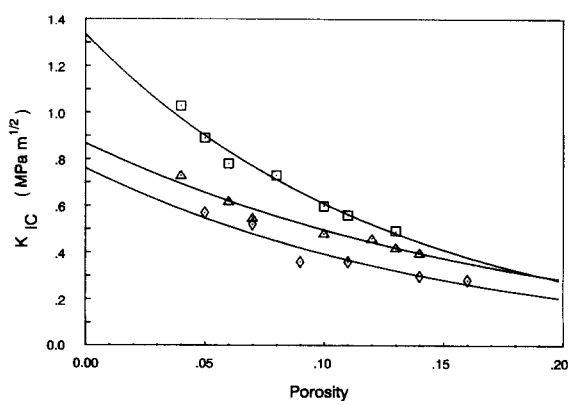

Fig. 2. Graphs of K_{IC} vs porosity for Avicel PH101 (△); Avicel PH102 (◊); Avicel PH105 (□).

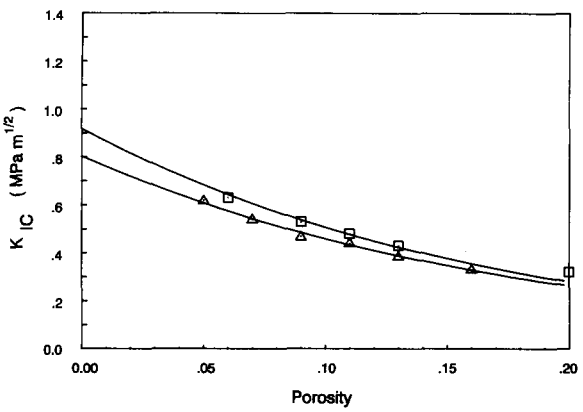

Fig. 3. Graphs of K_{IC} vs porosity for Emcocel (⊡); Emcocel 90M(△).

It is obvious from the results that the relationship between K_{IC} values and porosity is not linear, as suggested by Mashadi and Newton (1987a,b, 1988) and hence on extrapolation to zero porosity will lead to an underestimation of K_{IC0}. Relationships between the mechanical properties of materials and porosity have been extensively examined by Phani and Niyogi (1987) and it is appropriate to apply these types of relationships to our data. Two equations were tested; a simple exponential (Eqn 3) as used by Spriggs (1961) and a polynomial (Eqn 4) as used by Spinner et al. (1963):

$$K_{IC} = K_{IC0}\exp(-b\varepsilon) \tag{3}$$

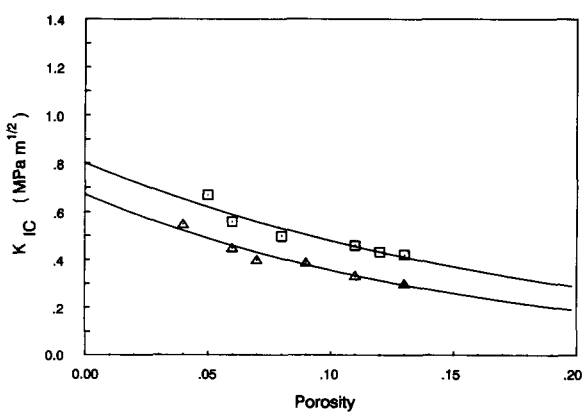

Fig. 4. Graphs of K_{IC} vs porosity for Unimac MG100 (⊡); Unimac MG200 (△).

$$K_{IC} = K_{IC0}(1-\varepsilon f_1 + \varepsilon f_2^2) \tag{4}$$

where ε is the porosity and b, f, and f_2 are constants reflecting the rate of change of K_{IC} with porosity.

For both relationships the low standard errors and the high correlation coefficients indicate a good fit to the data (see Table 3).

In Spriggs' work relating the modulus of powders and porosity (Spriggs, 1961) the constant b was associated with the proportion of open and closed pores present in the samples. High values were thought to indicate larger numbers of open pores compared to closed pores. The values of b reported in Table 3 are large compared with literature values, suggesting that open pores exhibit a stronger influence on the mechanical properties of these materials than closed pores.

Whilst there is some measure of agreement between values of K_{IC0} between the samples (Table 3) indicating a semi-brittle classification, real differences exist between the chemically equivalent materials. In addition there is also a particle size effect in that, for each of the three sources of material, the K_{IC0} values increased with decreasing particle size. A similar effect has been seen with notched beams of Al_2O_3 (Simpson 1973) who suggested that this was a consequence of the effect of the particle size of the powder on the properties on the beam itself. It may be that the differences in K_{IC0} can be attributed to the result of alternative manufacturing conditions and/or variation in the degree of crystalline order in the samples. It is interesting to note that in previous work (Bassam et al., 1989) the Young's modulus value for Avicel PH105 was also higher than for other microcrystalline cellulose samples examined.

Comparison of data

An interesting point with respect to the K_{IC0} values for Avicel PH101 reported here is that they are consistently lower than those given in the literature measured using a variety of other techniques (1.21 MPa $m^{1/2}$ by four-point beam bending (Mashadi and Newton, 1987b); 1.81 MPa $m^{1/2}$ by a radially edge cracked disc method (Roberts and Rowe, 1989)). This is despite the fact that the test

TABLE 3

Critical stress intensity factors at zero porosity (K_{IC0})

Material		Size (μm)[a]	K_{IC0} (MPa $m^{1/2}$)	b	CC	SE
Eqn 3	Avicel PH102	90	0.76	6.61	0.956	0.0947
	Avicel PH101	50	0.87	5.59	0.984	0.0430
	Avicel PH105	20	1.33	7.85	0.990	0.0418
	Emcocel 90M	90	0.80	5.59	0.997	0.0209
	Emcocel	56	0.92	5.92	0.980	0.0876
	Unimac MG200	103	0.67	6.37	0.978	0.0502
	Unimac MG100	38	0.80	5.16	0.959	0.0567

Material		Size (μm)[a]	K_{IC0} (MPa $m^{1/2}$)	f_1	f_2	CC	SE
Eqn 4	Avicel PH102	90	0.91	8.61	26.92	0.973	0.353
	Avicel PH101	50	0.99	7.77	25.90	0.991	0.0199
	Avicel PH105	20	1.42	8.60	27.81	0.988	0.0366
	Emcocel 90M	90	0.83	5.78	12.85	0.997	0.0110
	Emcocel	56	0.80	3.92	3.60	0.992	0.0247
	Unimac MG200	103	0.76	8.35	28.94	0.984	0.0206
	Unimac MG100	38	1.05	9.61	39.15	0.975	0.0273

[a]Manufacturers' data.

procedure, when validated with beams of polymethylmethacrylate, gave data comparable with literature figures (1.2 MPa $m^{1/2}$ (Kendall and Gregory, 1987)).

The reasons for the discrepancy in results from different test procedures have been extensively studied by Munz (1983). Basically, the problem lies in the difficulties in introducing two-dimensioned sharp cracks into a specimen and accurately measuring their lengths and velocity on the application of load. Ideally, K_{IC} should be independent of crack length and for these materials which exhibit a flat crack growth resistance curve all methods of measurement should produce equivalent data for K_{IC0}. However, many materials, especially ceramics, have been shown to exhibit a rising crack growth resistance curve and hence the method of crack induction and notch geometry become critical. For these materials measurements on specimens with a sawn or machined notch will always produce lower values of K_{IC} than those where the crack is introduced by a controlled flaw. This is the case for the double torsion method or the radially edge-cracked disc since in these two the total amount of crack extension at maximum load will always be larger. Direct evidence that Avicel PH101 is a material with a rising crack growth resistance curve can be obtained by reference to the work of Roberts and Rowe (1989) who showed that for radially edge-cracked discs crack growth resistance did not only change with crack size but also with specimen porosity and method of loading. For instance, for specimens produced at 16.9% porosity and loaded under diametrical compression, K_{IC} values varied from 0.66 to 2.38 MPa $m^{1/2}$ for crack lengths ranging from 2.75 to 9.55 mm.

It is evident from the above that K_{IC} cannot be regarded as a unique material constant and is simply one point on a crack growth resistance curve (Frieman, 1983) and hence will be dependent on specimen geometry and loading rate. This does not mean that the data generated in this work are invalid and that the effect of particle size/processing conditions of microcrystalline cellulose cannot be evaluated. In fact, it has been shown by Pratt (1977) that provided the methodology is kept constant such factors can be studied. However, if a definitive value of K_{IC} is required for comparison with other materials individual crack growth resistance curves need to be investigated such that all materials can be compared under the same conditions.

References

Bassam, F., York, P., Rowe, R.C. and Roberts, R.J., Effect of particle size and source on variability of Young's modulus of microcrystalline cellulose. *J. Pharm. Pharmacol.*, 40 (1988) Suppl. 68P.

Bassam, F., York. P., Rowe, R.C. and Roberts, R.J., Prediction of Young's modulus of binary powder mixtures. *J. Pharm. Pharmacol.*, 41 (1989) Suppl. 29P.

Brown, E.W. and Srawley, J.E., Plane strain crack toughness testing of high strength metallic materials. *ASTM Special Tech. Publ. No* 410 (1969).

Frieman, S.W., A critical evaluation of fracture mechanics techniques for brittle materials. In Bradt, R.C., Evans, A.G., Hasselman, D.P.H. and Lange, F.F. (Eds), *Fracture Mechanics of Ceramics*, Vol. 6, *Measurements, Transformations and High-Temperature Fracture*, Plenum, New York, 1983, pp. 27–45.

Kendall, K. and Gregory, R.D., Fracture of radially edge-cracked discs. *J. Mater. Sci.*, 22 (1987) 4514–4517.

Mashadi, A.M. and Newton, J.M., Assessment of the mechanical properties of compacted sorbitol instant. *J. Pharm. Pharmacol.*, 39 (1987a) Suppl. 67P.

Mashadi, A.M. and Newton, J.M., The characterisation of the mechanical properties of microcrystalline cellulose; a fracture mechanics approach. *J. Pharm. Pharmacol.*, 39 (1987b) 961–965.

Mashadi, A.M. and Newton, J.M., Determination of the critical stress intensity factor (K_{IC}) of compacted pharmaceutical powders by the double torsion method. *J. Pharm. Pharmacol.*, 40 (1988) 597–600.

Munz, D., Effect of specimen type on the measured values of fracture toughness of brittle ceramics. In Bradt, R.C., Evans, A.G., Hasselman, D.P.H. and Lange, F.F. (Eds), *Fracture Mechanics of Ceramics*, Vol. 6, *Measurements, Transformations and High-Temperature Fracture*, Plenum, New York, 1983, pp. 1–26.

Phani, K.K. and Niyogi, S.K., Elastic modulus-porosity relationship for Si_3N_4. *J. Mater. Sci. Lett.*, 6 (1987) 511–515.

Pratt, P.L., Grain-size and fracture toughness of alumina. In Taplin, D.M.R. (Ed.), *Adv. Res. Strength Fract. Mater., 4th Int. Conf. Fract.*, 1978, Pergamon, New York, Vol. 3B, pp. 909–912.

Roberts, R.J. and Rowe, R.C., Brittle/ductile behaviour in pharmaceutical materials used in tabletting. *Int. J. Pharm.*, 36 (1987) 205–209.

Roberts, R.J. and Rowe, R.C., Source and batchwise variability in the compressibility of microcrystalline cellulose. *J. Pharm. Pharmacol.*, 40 (1988) Suppl. 70P.

Roberts, R.J. and Rowe, R.C., Determination of the critical stress intensity factor (K_{IC}) of microcrystalline cellulose using radially edge-cracked tablets. *Int. J. Pharm.*, 52 (1989) 213–219.

Roberts, R.J., Rowe, R.C. and Kendall, K., Brittle-ductile transitions in die compaction of sodium chloride. *Chem. Eng. Sci.*, 44 (1989) 1647–1651.

Simpson, L.A., Effect of microstructure on measurements of fracture energy of Al_2O_3. *J. Am. Ceram. Soc.*, 56 (1973).

Spinner, S., Knudsen, F.P. and Stone, L., Elastic constant – porosity relations for polycrystalline thoria. *J. Res. Natl. Bureau Stand. (Eng. Instr.)*, 67C (1963) 39–46.

Spriggs, R.M., Expression for effect of porosity on elastic modulus of polycrystalline refactory materials, particularly aluminium oxide. *J. Am. Ceram. Soc.*, 44 (1961) 628–629.

Wiederhorn, S.M., Influence of water vapor on crack propogation in soda-lime glass. *J. Am. Ceram. Soc.*, 50 (1967) 407–414.