International Journal of Pharmaceutics, 86 (1992) 49–58
Elsevier Science Publishers B.V.

IJP 02858

The effect of some formulation variables on crack propagation in pigmented tablet film coatings using computer simulation

R.C. Rowe and R.J. Roberts

ICI Pharmaceuticals, Alderley Park, Macclesfield SK10 2NA (UK)

(Received 15 November 1991)
(Accepted 17 March 1992)

Key words: Crack propagation; Film coating; Simulation; Pigment; Fracture

Summary

A model originally developed to simulate crack propagation in structural steel and recently shown to be applicable to pigmented tablet film coatings has been used to study the effect on crack propagation of some specific formulation variables such as the addition of plasticizers to the polymer, the use of higher molecular weight polymer, the addition of a second population of a pigment of larger particle size and the breadth of the particle size distribution of the pigment. Simulations investigating plasticizer addition and the effect of polymer molecular weight confirm that both would be beneficial in alleviating the problems of cracking as found in practice although in the former the mechanism operates by increasing the critical strain energy release rate rather than increasing the critical stress intensity factor of the system. The addition of a second population of a pigment of larger particle size and the broadening of the size distribution of the pigment both result in a decrease in crack velocity thus providing an alternative, although as yet unproven, method for alleviating cracking. The program is easy to use enabling many simulations to be performed with minimum effort.

Introduction

Solid inclusions in the form of aluminium lakes of water soluble dyes, opacifiers (e.g., titanium dioxide) and various inorganic materials (e.g., iron oxides, calcium carbonate, talc, colloidal silica) are often added to tablet film coatings to improve their appearance (e.g., colour and opacity), barrier properties and, in some cases, their film-forming characteristics (Rowe, 1984). However, because of the large differences between their thermal expansion coefficients and those of the polymer film (Rowe, 1982b), such materials can act as local stress concentrators promoting crack initiation leading, in some cases, to catastrophic propagation resulting in the defects cracking and edge splitting and peeling (Rowe and Forse, 1980). These defects can have profound effects on the release of an active ingredient especially if the tablet has been coated with an entero-soluble or sustained release film.

Although the statics of this complex phenomena are now relatively well understood (Rowe, 1986b) it is only recently that the dynamics have been investigated (Rowe and Roberts, 1992). In this study, the same model and computer simulation as described by Rowe and Roberts (1992) has been used to investigate the effect on crack

---

Correspondence to: R.C. Rowe, ICI Pharmaceuticals, Alderley Park, Macclesfield, Cheshire SK10 2NA, U.K.

propagation in pigmented tablet film coatings of some specific formulation variables such as the addition of plasticizers to the polymer, the use of a higher molecular weight polymer, the addition of a second population of inclusions (pigments) of a larger particle size and the breadth of the particle size distribution of the inclusion. Where possible the resultant predictions have been interpreted in terms of the practical situation.

The Model

The model used in this study was originally developed to simulate crack propagation in structural steels (Broberg, 1990) but as shown by Rowe and Roberts (1992) is equally applicable to pigmented tablet film coatings. Although the model has been described in detail previously (Broberg 1989, 1990; Rowe and Roberts, 1992) it is important, in the context of this study, to reiterate the following:

(1) The fracture mechanism is assumed to consist of hole formation, growth and coalescence where holes are opened and grow around the inclusion according to a viscosity rule (Broberg, 1990),

$$\frac{1}{R}\cdot\frac{\mathrm{d}R}{\mathrm{d}t}=\beta\left(\frac{\sigma}{\sigma_0}-1\right)^2\left[1+\left(\frac{\sigma}{\sigma_0}-1\right)^n\right] \quad (1)$$

where σ, the stress at the hole (calculated from a complex expression involving a knowledge of K_{IC} the critical stress intensity and C_d the irrotational wave velocity (Broberg (1990)) is always greater than σ_0 the flow or yield stress of the polymer matrix, R denotes the radius of the inclusion/hole, t is the time, β represents the fluidity (i.e., the reciprocal of the viscosity) of the polymer matrix and n is an exponent.

(2) The inclusions are assumed to be spherical of a specified mean particle size with a variable standard deviation (expressed as a fraction of the mean). The position of the inclusions is randomly distributed and up to two populations of different sizes can be accommodated.

(3) In the simulation the inclusions are displayed on the computer screen as circles (scaled to include 100 particles) and hole growth by drawing the new periphery for each step. Coalescence and crack formation between two holes is simply marked by a straight line between the centres.

Experimental

The program asks for an input of the mean inclusion diameter of each of the two populations, the intended volume fraction of each of the two populations, and values for the yield stress, fluidity, exponent, irrotational wave velocity and stress intensity factor for the polymer matrix. In addition, the size distribution of the inclusions can be specified. Unfortunately, accurate values for all parameters are not available but it is possible to estimate these using known data and scaling factors (Rowe and Roberts, 1992). The input data for the simulations undertaken in this study are listed in Tables 1–4.

TABLE 1

Values for parameters used to investigate effect of plasticizer concentration

Parameter	Values used in simulations		
Plasticizer concentration (% w/w)	0	10	20
Young's modulus of elasticity (MPa)	2149	1712	1219
Yield stress (MPa)	30	25.8	20.8
Fluidity (s^{-1})	10^5	8×10^4	6×10^4
Irrotational wave velocity ($m\ s^{-1}$)	1390	1241	1041
Exponent	1	1	1
Critical stress intensity factor ($MPa\ m^{1/2}$)	← 0.1–0.4 →		
Mean size of inclusions (μm)	1	1	1
Standard deviation (fraction of mean)	0.1	0.1	0.1
Volume fraction (%)	12.2	12.2	12.2

TABLE 2

Values for parameters used to investigate effect of polymer molecular weight

Parameter	Values used in simulations	
Nominal viscosity grade of polymer (mPa)	6	50
Young's modulus of elasticity (MPa)	2 149	2 515
Yield stress (MPa)	30	40.2
Fluidity (s^{-1})	10^5	1.2×10^4
Irrotational wave velocity ($m\ s^{-1}$)	1 390	1 504
Exponent	1	1
Critical stress intensity factor ($MPa\ m^{1/2}$)	← 0.1–0.5 →	
Mean size of inclusions (μm)	1	1
Standard deviation (fraction of mean)	0.1	0.1
Volume fraction (%)	12.2	12.2

The data in Table 1 represent parameters for a formulation of hydroxypropyl methylcellulose (of nominal viscosity grade 6 mPa s) plasticized with increasing concentration of polyethylene glycol 400 containing 12.2% by volume of a red iron oxide pigment of relative narrow size distribution. The yield stresses have been calculated using a scaling factor taken from hardness measurements using microindentation (Rowe, 1976) and the irrotational wave velocities and fluidity parameter using scaling factors taken from measurements of the modulus of elasticity of free films (Gibson et al., 1988a; Rowe and Roberts, 1992). Similar methods have been used to calculate data for the higher molecular weight polymer (representing hydroxypropyl methylcellulose of nominal viscosity grade 50 mPa s) shown in Table 2.

TABLE 3

Values of parameters used to investigate effect of the introduction of a second inclusion

Parameter	Values used in simulation
Young's modulus of elasticity (MPa)	2 149
Yield stress (MPa)	30
Fluidity (s^{-1})	10^5
Irrotational wave velocity ($m\ s^{-1}$)	1 390
Exponent	1
Critical stress intensity factor ($MPa\ m^{1/2}$)	← 0.1–0.7 →
Mean size of small inclusion (μm)	0.25
Mean size of large inclusion (μm)	3.0
Standard deviation (fraction of mean)	0.1
Volume fraction of small inclusion (%)	variable
Volume fraction of large inclusion (%)	variable
Total volume fraction (%)	12.0 ± 1

TABLE 4

Values of parameters used to investigate effect of particle size distribution of inclusions

Parameter	Values used in simulation
Young's modulus of elasticity (MPa)	2 149
Yield stress (MPa)	30
Fluidity (s^{-1})	10^5
Irrotational wave velocity ($m\ s^{-1}$)	1 390
Exponent	1
Critical stress intensity factor ($MPa\ m^{1/2}$)	0.3 and 0.5
Mean size of inclusions (μm)	0.25–3.0
Standard deviation (fraction of mean)	0–2.0
Volume fraction (%)	16.2

The data in Table 3 represent parameters for a formulation consisting of hydroxypropyl methylcellulose (of nominal viscosity grade 6 mPa s) pigmented with titanium dioxide (mean particle size 0.25 μm) to which has been added an increasing proportion of an aluminium lake of a coloured dye (mean particle size 3 μm) at a constant total pigment volume concentration of 12 ± 1%. The data in Table 4 represent parameters for the same polymer pigmented with pigments of varying mean particle size with varying distributions (as indicated by a change in the standard deviation of the mean) at a constant volume fraction of 16.2%.

In all cases the exponent was assumed to be unity (Rowe and Roberts, 1992) and randomisation of inclusions was kept constant to enable simulations to be directly compared.

Observations

Effect of plasticizer concentration

Fig. 1 shows pooled data illustrating the effect of plasticizer concentration on crack velocity and

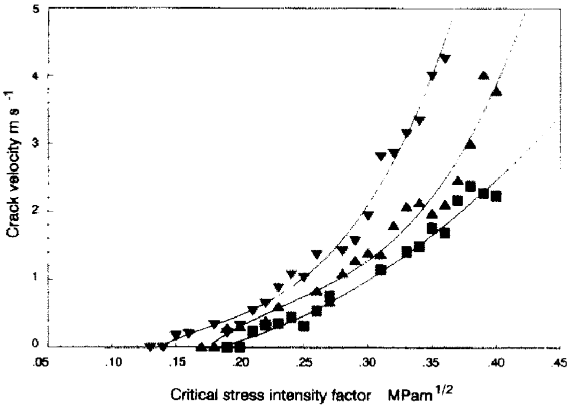

Fig. 1. Effect of increasing plasticizer concentration on the relationship between crack velocity and critical stress intensity factor for a polymer film containing 12.2% by volume of a red iron oxide pigment. Plasticizer concentration: (■) 0%; (▲) 10%; (▼) 20%.

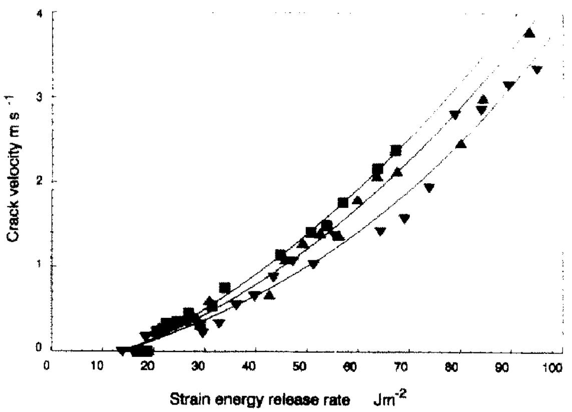

Fig. 2. Effect of increasing plasticizer concentration on the relationship between crack velocity and strain energy release rate for a polymer film containing 12.2% by volume of a red iron oxide pigment. Plasticizer concentration: (■) 0%; (▲) 10%; (▼) 20%.

critical stress intensity factor. The critical stress intensity factor describes the state of stress around an unstable crack and is thus an indication of the stress required to produce catastrophic propagation of the crack. Hence, the inference from the data is that addition of a plasticizer results in a system where crack propagation is exacerbated. This would appear to be somewhat anomalous since it is well known that the addition of plasticizers is beneficial in alleviating the problems of cracking in film coated tablets (Rowe, 1981; Okhamafe and York, 1985). However, if the data are reappraised in terms of the critical strain energy release rate G_{IC} (a measure of the energy necessary for crack initiation) where G_{IC} and K_{IC} are related by the equation,

$$G_{IC} = \frac{K_{IC}^2}{E} \qquad (2)$$

where E is the Young's modulus of elasticity, then the opposite inference can be drawn (Fig. 2). The overall conclusion, therefore, is that the addition of plasticizers increases the energy necessary to initiate a crack but once cracking occurs propagation will be faster. The relative dominance of the two effects in any one system will govern the overall effect on the incidence of cracking and accounts for the somewhat variable data reported in manufacturer's literature of the effect of different plasticizers on film cracking (Rowe, 1982a).

Effect of polymer molecular weight

Figs 3 and 4 show pooled data on the effect of increasing polymer molecular weight on crack velocity and both the critical stress intensity factor and strain energy release rate. The overall conclusion is that increasing the polymer molecu-

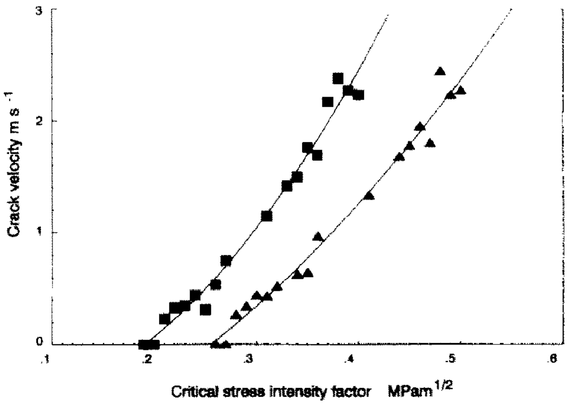

Fig. 3. Effect of increasing molecular weight on the relationship between crack velocity and critical stress intensity factor for polymer film consisting of hydroxypropyl methylcellulose containing 12.2% red iron oxide pigment. Nominal viscosity grade: (■) 6 mPa s; (▲) 50 mPa s.

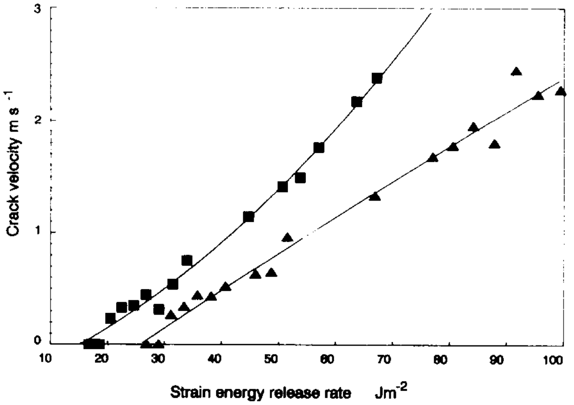

Fig. 4. Effect of increasing molecular weight on the relationship between crack velocity and strain energy release rate for polymer film consisting of hydroxypropyl methylcellulose containing 12.2% red iron oxide pigment. Nominal viscosity grade: (■) 6 mPa s; (▲) 50 mPa s.

lar weight results in a tougher film where even if a crack is initiated, propagation will be very slow, i.e., this formulation change is unequivocally beneficial as indeed has been shown in practice for formulations based not only on hydroxypropyl methylcellulose (Rowe and Forse, 1980) but also on hydroxypropyl methylcellulose phthalate (Rowe, 1982c) and ethylcellulose (Rowe, 1986a).

Effect of adding large inclusions

Simulations for a system containing all small particles and one containing a ratio of 9 : 1 by volume of large to small particles at constant volume concentration of 12 ± 1% and a critical stress intensity factor of 0.5 MPa $m^{1/2}$ are shown in Figs 5 and 6. It can be seen that the addition of the large particles results in a different crack route – propagation taking place primarily via the large particles although some small particles are included. In addition, there is less divergence from the main crack and a disappearance of small cracks independent of the main crack. In the simulations shown crack velocity was decreased by approx. 50% from 11.9 to 5.5 m s^{-1} after the addition of the large particles. The decrease in crack velocity is dependent on the volume concentration of the large particles but independent of the critical stress intensity factor (Fig. 7). This would imply that the addition of a second population of large inclusions in a film formulation would be beneficial in reducing the incidence of

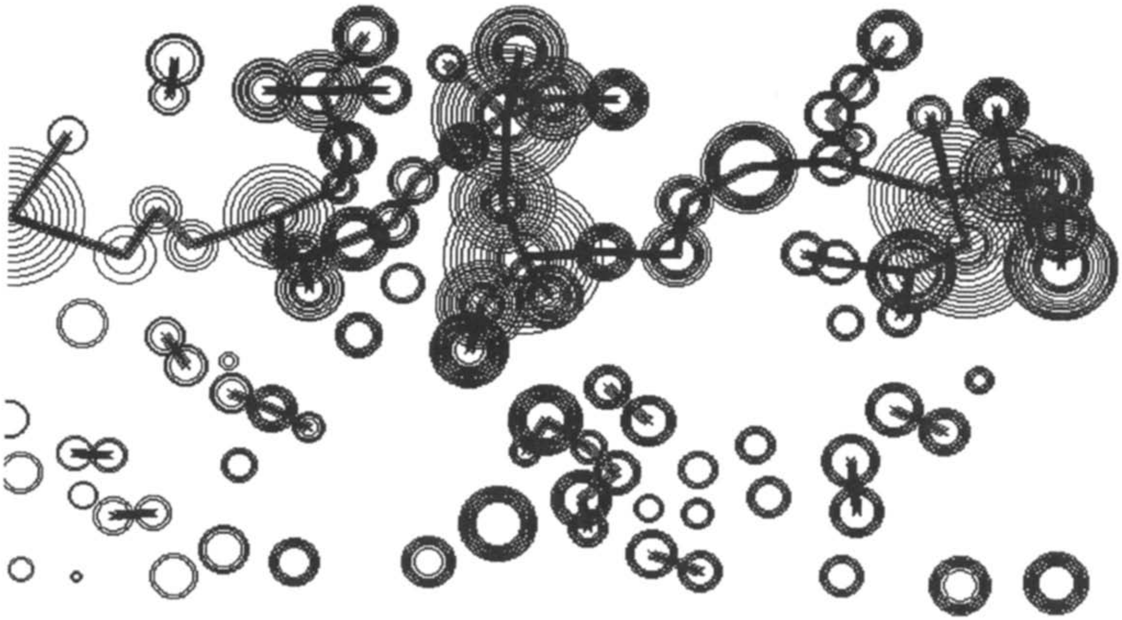

Fig. 5. Simulation of a system containing 12.2% by volume of an inclusion of mean size 0.25 μm assuming a stress intensity factor of 0.5 MPa $m^{1/2}$.

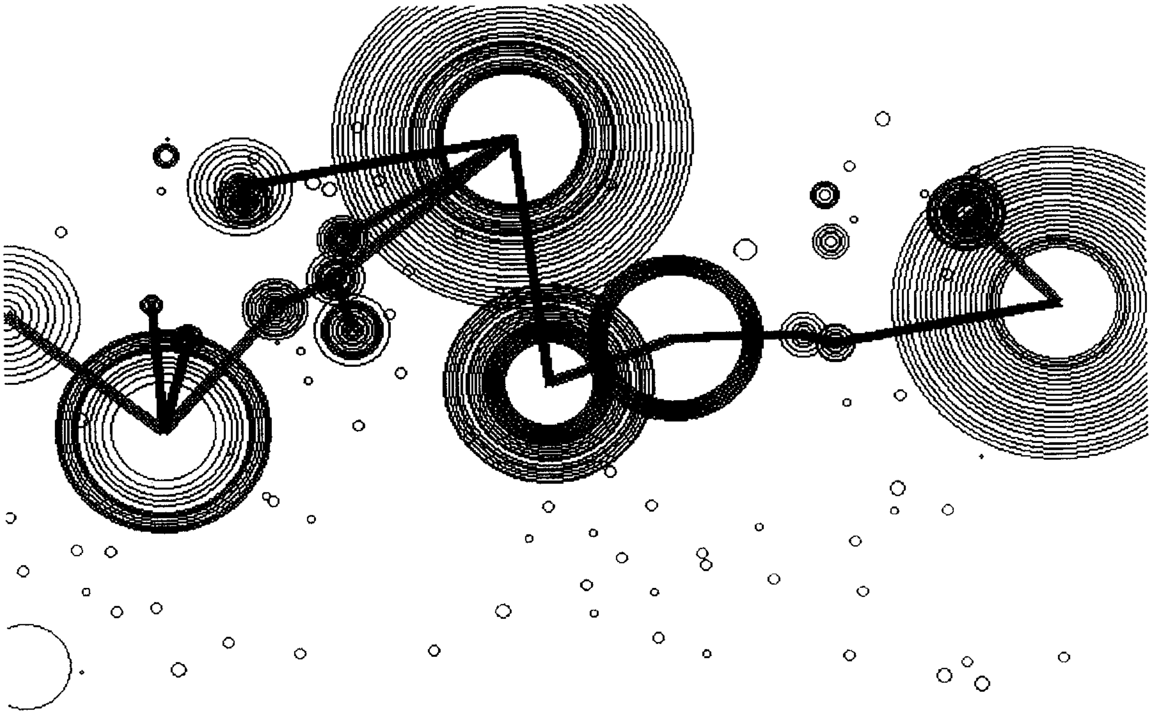

Fig. 6. Simulation of a mixed system of total inclusion volume 12.2% consisting of 9.8% of an inclusion of mean size of 0.25 μm and 90.2% of an inclusion of mean size 3 μm assuming a stress intensity factor of 0.5 MPa $m^{1/2}$.

cracking. Unfortunately, no experimental data exist despite the fact that many film coating formulations contain mixtures of coloured pigments and titanium dioxide.

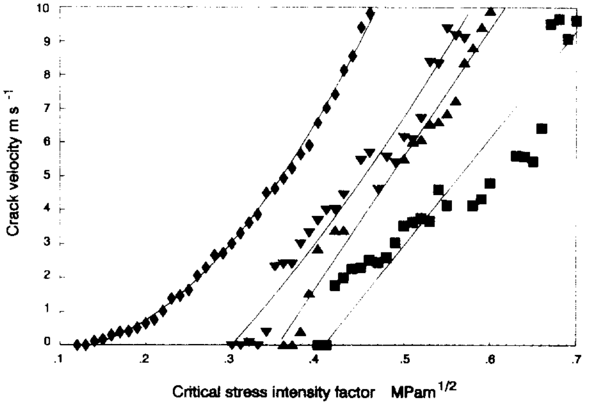

Fig. 7. Effect of introducing various percentages of a second inclusion on the relationship between crack velocity and critical stress intensity factor for polymer film containing titanium dioxide and red iron oxide of total volume 12 ± 1%. Percentage ratios: (◆) 100/0; (▼) 21.5/78.5; (▲) 9.8/90.2; (■) 0/100.

Effect of particle size distribution

Simulations for a system containing particles of 1 μm mean diameter but varying distribution at a constant volume concentration of 16.2% and critical stress intensity factor of 0.5 MPa $m^{1/2}$ are shown in Figs 8–11. The effect of broadening the distribution is similar to that seen on the addition of a second population of larger particles (Figs 5 and 6), i.e., a change in the crack route, less divergence from the main crack and a decrease in

TABLE 5

Effect of mean size of inclusions and the standard deviation (fraction of mean) on crack velocity for a critical stress intensity factor of 0.3 MPa $m^{1/2}$

Standard deviation	Crack velocity (m s^{-1})		
	0.25 μm	0.5 μm	1.0 μm
0	3.21	2.06	0.74
0.25	2.50	1.20	0.52
0.5	2.41	1.00	0.49
1.0	1.64		
2.0	0.72		

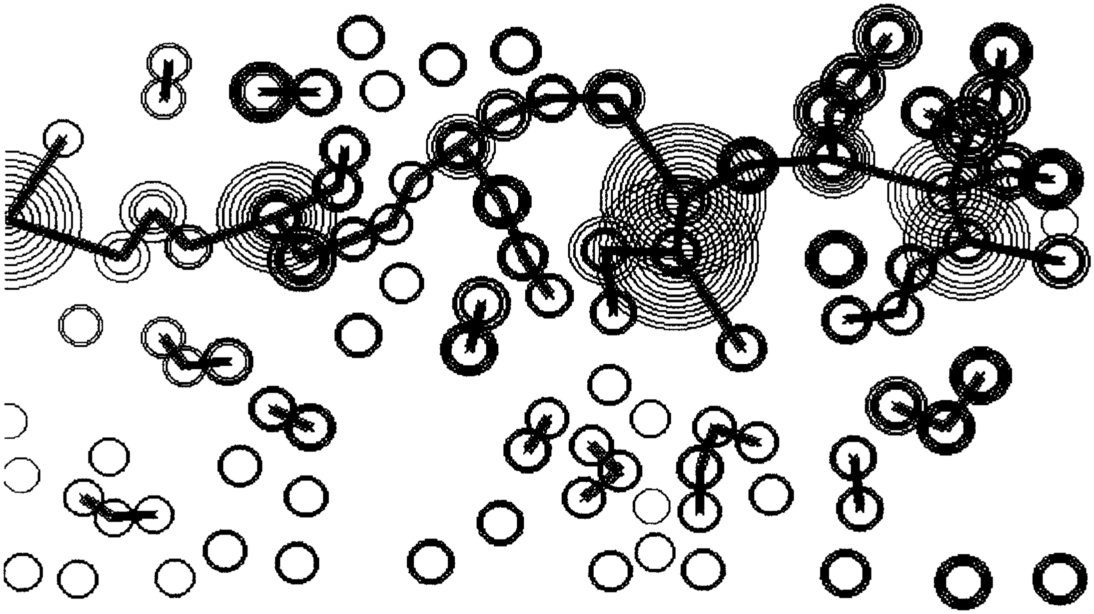

Fig. 8. Simulation of a system containing 16.2% by volume of an inclusion of mean size 1 μm with a standard deviation of 0, assuming a stress intensity factor of 0.5 MPa m$^{1/2}$.

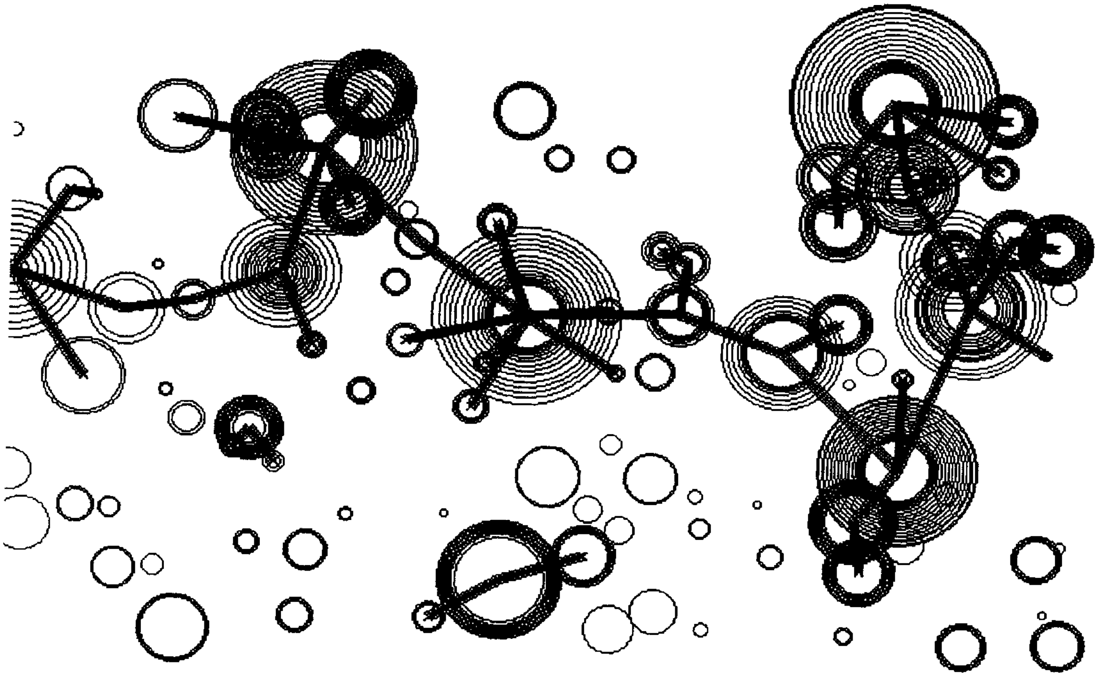

Fig. 9. Simulation of a system containing 16.2% by volume of an inclusion of mean size 1 μm with a standard deviation of 0.5, assuming a stress intensity factor of 0.5 MPa m$^{1/2}$.

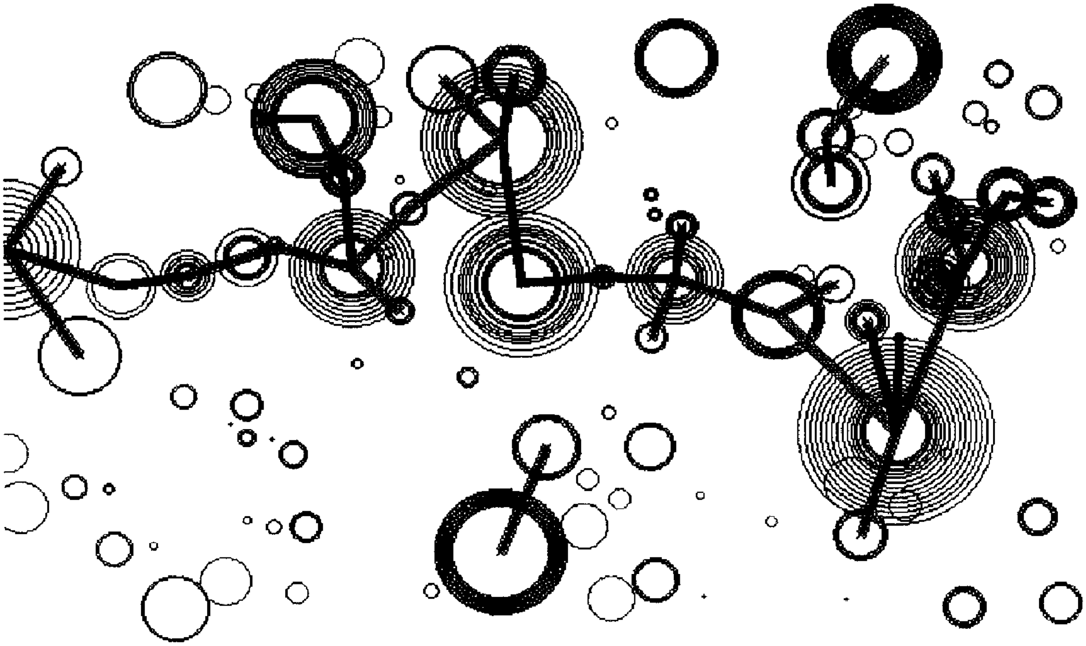

Fig. 10. Simulation of a system containing 16.2% by volume of an inclusion of mean size 1 μm with a standard deviation of 1.0, assuming a stress intensity factor of 0.5 MPa $m^{1/2}$.

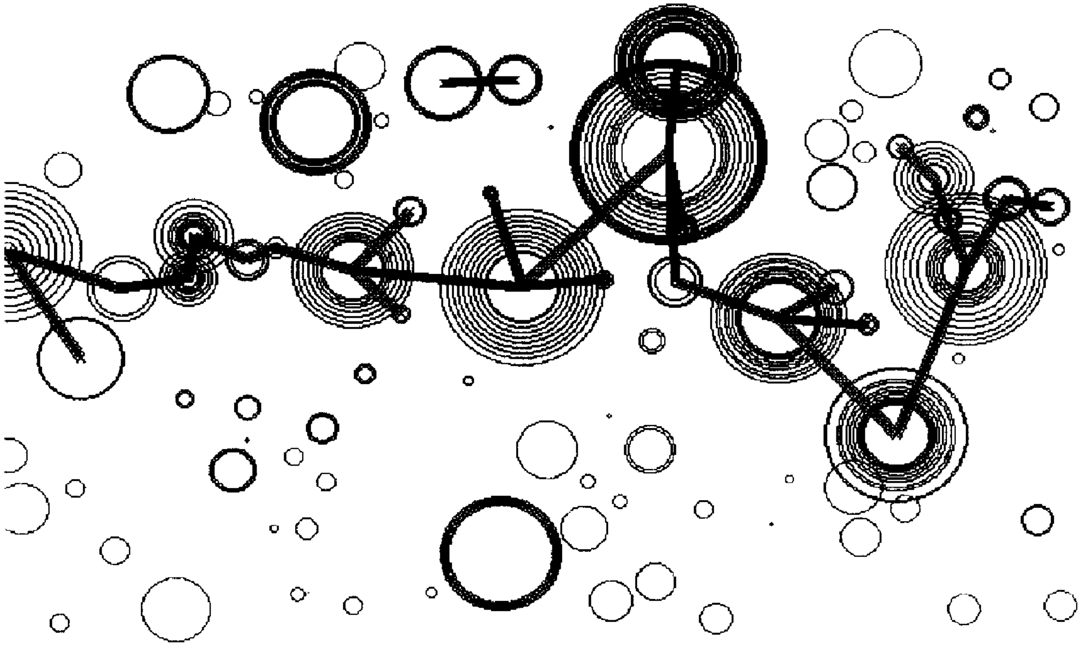

Fig. 11. Simulation of a system containing 16.2% by volume of an inclusion of mean size 1 μm with a standard deviation of 2.0, assuming a stress intensity factor of 0.5 MPa $m^{1/2}$.

TABLE 6

Effect of mean size of inclusions and the standard deviation (fraction of mean) on crack velocity for a critical stress intensity factor of 0.5 MPa $m^{1/2}$

Standard deviation	Crack velocity (m s^{-1})				
	0.25 μm	0.5 μm	1.0 μm	2.0 μm	3.0 μm
0	12.72	10.36	6.75	3.44	2.98
0.25	12.23	9.16	5.28	1.68	2.23
0.5	11.58	8.78	4.46	1.81	1.80
1.0	7.84	4.46	2.26	1.16	–
2.0	6.57	3.10	0.62	–	–

the number of small cracks independent of the main crack. In addition, crack velocity decreases (Tables 5 and 6). An interesting point to note is that the decrease in crack velocity seen on broadening the distribution from 0 to 2 for particles of mean diameter either 0.25 or 0.5 μm is approximately equivalent to that observed on increasing the mean diameter by a factor of 4. Unfortunately, no experimental data for film formulations to confirm this finding in practice are available, probably due to the fact that it is extremely difficult to accurately size pigments in the sub-micron range. What data there are show relatively wide distributions for the iron oxides (Rowe, 1985).

Conclusion

The data generated in this study fully support the conclusions drawn in the previous investigation, i.e., despite the many simplifications of a very complex phenomenon, the program appears to adequately simulate the process of crack propagation in a pigmented film coating and can be used to study consequences of changes in formulation variables. The agreement with experimental observations is extremely good. A specific deficiency in the treatment is the absence of any way to simulate the effect of bonding at the pigment/polymer matrix interface due to specific physico-chemical interactions. This would require a strain criterion for hole formation but cannot be incorporated in the present treatment (Broberg, 1990). Fortunately, for hydroxypropyl methylcellulose films as simulated in this study, only titanium dioxide would appear to exert any degree of interaction (Gibson et al., 1988b).

Acknowledgement

The authors wish to express their gratitude to Professor K.B. Broberg for his invaluable advice.

References

Broberg, K.B., Material behaviour at rapid loading – old thoughts revisited. In Jinghong, F. and Murakami, S. (Eds), *Advances in Constitutive Laws for Engineering Materials*, Pergamon, Oxford, 1989, Vol. 1, pp. 255–358.

Broberg, K.B., Computer demonstration of crack growth. *Int. J. Fracture*, 42 (1990) 277–285.

Gibson, S.H.M., Rowe, R.C. and White, E.F.T., Mechanical properties of pigmented tablet coating formulations and their resistance to cracking. I: Static mechanical measurement. *Int. J. Pharm.*, 48 (1988a) 63–77.

Gibson, S.H.M., Rowe, R.C. and White, E.F.T., Quantitative assessment of additive-polymer interaction in pigmented hydroxypropyl methylcellulose formulations using immersion calorimetry. *Int. J. Pharm.*, 48 (1988b) 113–117.

Okhamafe, A.O. and York, P., Stress crack resistance of some pigmented and unpigmented tablet film coating systems. *J. Pharm. Pharmacol.*, 37 (1985) 449–454.

Rowe, R.C., Microindentation – a method for measuring the elastic properties and hardness on conventionally coated tablets. *J. Pharm. Pharmacol.*, 28 (1976) 310–311.

Rowe, R.C., The cracking of film coatings on film-coated tablets - a theoretical approach with practical implications. *J. Pharm. Pharmacol.*, 33 (1981) 423–426.

Rowe, R.C., Some fundamental properties of polymeric materials and their application in film coating formulations – A review. *Int. J. Pharm. Tech. Prod. Mfr.*, 3 (1982a) 3–8.

Rowe, R.C., A comment on the localised cracking around pigment particles in film coatings applied to tablets. *Int. J. Pharm. Tech. Prod. Mfr.*, 3 (1982b) 67–68.

Rowe, R.C., Molecular weight studies on hydroxypropyl methylcellulose phthalate (HP55). *Acta Pharm. Technol.*, 28 (1982c) 127–130.

Rowe, R.C., Materials used in the film coating of oral dosage forms. *Crit. Rep. Appl. Chem.*, 6 (1984) 1–36.

Rowe, R.C., The effect of the particle size of red iron oxide on the appearance of tablet film coatings. *Pharm. Acta. Helv.*, 60 (1985) 157–161.

Rowe, R.C., The effect of the molecular weight of ethylcellulose on the drug release properties of mixed films of ethylcellulose and hydroxypropyl methylcellulose. *Int. J. Pharm*, 29 (1986a) 37–41.

Rowe, R.C., Localised cracking around pigment particles in tablet film coating - a theoretical approach. *J. Pharm. Pharmacol.*, 38 (1986b) 529–530.

Rowe, R.C. and Forse, S.F., The effect of polymer molecular weight on the incidence of film cracking and splitting in film coated tablets. *J. Pharm. Pharmacol.*, 32 (1980) 583–584.

Rowe, R.C. and Roberts, R.J., Simulation of crack propagation in tablet film coatings containing pigments. *Int. J. Pharm.*, 78 (1992) 49–57.