Influence of Pigments and Processing on the Dimensions and Appearance of HDPE Injection-Moulded Bottle Caps

It is widely known that some organic pigments, such as phthalocyanines, have a mixed reputation within the moulding industry. Despite their low cost, excellent colouring ability and lightfastness these pigments cause problems with unacceptable levels of shrinkage and distortion in mouldings manufactured from commodity polymers, such as polypropylene and polyethylene. These pigments act as nucleating agents, raising the temperature of crystallisation and producing marked changes in microstructure. As a result, the size and shape of injection-moulded artefacts can vary according to the colour of the feedstock. This issue is of particular importance to manufacturers of closures, such as bottle caps and snap-fittings, which are often produced in a range of colours and contain tensioners and/or tamper-proof seals with tight dimensional tolerances.

This Measurement Note presents the results from a study on the dimensions and appearance of a complex “real” component (bottle cap with tamper-proof seal) produced using different pigmented feedstocks and under different processing conditions. The effects of hold time and pressure, injection time and pressure, and mould and melt temperatures were considered. A design of experiments (DoE) approach was used to evaluate the impact of theses factors on the mouldings produced. A summary of the implementation, observations, important results and principal conclusions of this investigation is provided.

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May 2002

INTRODUCTION

Some organic pigments, such as phthalocyanines, have a reputation within the moulding industry for causing problems with unacceptable levels of shrinkage and distortion in mouldings manufactured from commodity polymers [1].

Several organic pigments have been shown to affect the crystallisation behaviour of polyolefins [2, 3] by acting as nucleating agents, raising the temperature at which crystallisation occurs and the nature (size and number) of the spherulites formed. Thus, the size and shape of injection-moulded artefacts can vary according to the colour of the feedstock.

This issue is of particular importance to manufacturers of closures which are often produced in a range of colours and require tight dimensional tolerances (<2%) to ensure functionality. Often, parts manufactured from feedstock containing different pigments have such widely different shrinkages that they no longer comply with design specifications.

The main causes of shrinkage are:

- volume changes during solidification
- crystallisation
- orientation.

Dimensional stability causes additional problems in continuous production cycles where excessive shrinkage of the moulding onto the mould tool can cause machines to jam. Solutions devised to accommodate this include:

- increasing the speed of ejection (pins/ compressed air)
- annealing in the mould.

This often leads to other problems, such as:

- localised distortion of the mouldings
- damage to sensitive features (e.g tamper-proof ring)
- increased cycle time and reduced productivity.

Statistically significant links have previously been demonstrated between both pigments and processing and the shrinkage/distortion of a simple plate moulding [4, 5, 6]. The behaviour of simple geometries is easily assessed but is often unrepresentative of industrially relevant mouldings. In this study, the effects of pigments and processing conditions on the size, shape and appearance of complex components are determined.

IMPLEMENTATION

Moulding Geometry

A split-thread bottle cap with pilfer-band, ∅30 mm x 20 mm tall, shown in Figure 1, was chosen as an example of a "real" component. The mouldings are characterised on the basis of the following properties:

- weight
- thickness
- colour intensity
- top flatness
- diameter
- cylindricity
- thread pitch and depth.

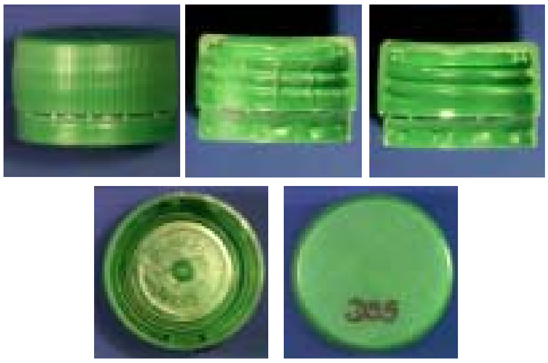

Figure 1 - Detailed moulding geometry.

Materials

Caps were moulded from HDPE (BP Rigidex) with three pigments, in addition to the unpigmented material used as a reference, at a pigment concentration of 0.6 wt% (+ 0.2 wt% slip), detailed in Table 1.

Table 1 – Pigment Details

Pigments	Code	Type
Phthalocyanine green	MB	Solid masterbatch
Phthalocyanine green	Pigment A	Liquid colorant
Blue and heat stable yellow (combined)	Pigment B	Liquid colorant

Processing Variables

The influence of a number of processing factors on the mouldings was considered:

- injection time
- injection pressure
- holding pressure
- holding time
- melt temperature
- mould temperature of hot external surface.

A suitable processing window was determined within which several discrete levels were selected as target values to be achieved for individual mouldings, as shown in Table 2.

Table 2 – Processing Window and Targets.

Processing Variable	Window Size	Target Values		
Inj time (% of max)	80 ± 5	75	80	85
Inj press (bar)	90 ± 30	65	90	115
Hold press (bar)	0 - 100	1	50	100
Hold time (s)	0 - 5	1	3	5
Melt temp (^{o}C)	245 ± 25	230	245	260
Mould temp – HS (^{o}C)	65 ± 10	57	65	72
		Low	**Medium**	**High**

A Boy 80M injection-moulding machine was used to mould the caps. Caps from one cavity of a four-cavity prototyping mould tool were used for the trials. The injection pressure was maintained at the target level along the whole length of the screw to avoid complications due to pressure gradients and the temperature of the hot runner feeds to each of the four cavities was set equal to the target melt temperature. The mould temperature on the cool internal surface of the cap and the cooling time were held constant throughout all the trials at 14 ^{o}C and 6 s, respectively.

Unfortunately the practicalities of the injection-moulding process make it very difficult to ensure that the machine-set target values are actually met in the cavity for a variety of reasons:

- lowering the holding time reduces the cycle time and causes the cavity wall temperature to rise as the cooling circuits attempt to dissipate a higher heat flux
- shear heating of the melt as it flows through the hot runner becomes increasingly significant with decreasing injection time, increasing injection pressure or due to the increased viscosity associated with a decrease in the melt temperature
- short injection times can result in melt compression, the subsequent decompression of which can cause either backflow or add an extra contribution to the holding pressure.

Virgin HDPE was used to purge the barrel between successive pigment changes. For each batch of moulded caps, the injection-moulding machine was allowed to run through at least five moulding cycles before conditions were deemed to be sufficiently stable for sample collection. Five caps were then produced for each set of conditions.

Trial Design

To consider all possible combinations of each factor investigated in this study, at each target value, in a full factorial array would require a very large number of runs, i.e. 972. This task can be made more manageable by using a design of experiments (DoE) approach which enables the selection of a statistically significant fractional subset of the full array (this can be achieved using commercial software), thus only a small number of factor combinations are considered.

The size of this array can be increased slightly to include interactions between factors which provide further important information on which of the variables are interrelated (i.e. have a greater influence in conjunction with another factor than

Table 3 – Design Matrix

Run	Hold Time	Hold Press	Mould Temp HS	Melt Temp	Inj Press	Inj Time
1	m	h	m	m	l	h
2	h	m	m	l	l	m
3	m	h	m	m	l	l
4	m	m	h	l	m	h
5	m	l	m	m	l	l
6	l	m	m	h	l	m
7	l	l	m	l	m	m
8	m	l	h	m	h	m
9	m	h	h	m	h	m
10	h	l	m	h	m	m
11	m	m	m	m	m	m
12	m	h	l	m	h	m
13	h	h	m	h	m	m
14	m	m	h	h	m	l
15	h	m	l	m	m	l
16	l	m	m	h	h	m
17	m	l	h	m	l	m
18	m	m	h	l	m	l
19	m	m	h	h	m	h
20	m	l	l	m	l	m
21	m	l	m	m	l	h
22	h	m	m	l	h	m
23	l	h	m	l	m	m
24	l	m	l	m	m	h
25	m	l	l	m	h	m

individually). The final D-optimal design is listed in Table 3 with the low, medium and high target values. These runs were repeated for each additional pigmented feedstock.

Several other factors may play a role but can not be controlled. These include:

- variations in target processing value within mould cavity (shear heating raises melt and mould temperatures, freeze-off shields hold pressure, etc)
- ejection air pressure
- amount and type of additives in different pigment formulations
- accumulation of slip residue in the mould cavity
- material degradation at high temperatures
- post-ejection cooling.

Moulding Trials

A pigmented trefoil pattern was observed when a new pigment was introduced following a virgin material purge, shown in Figure 2 (left). It is thought that the triangular internal structural support within the tip of the triverted hot runner, feeding each centre-gated cavity, is responsible. Residual traces of pigment after extensive purging with virgin material, seen in Figure 2 (right), also suggest that pigmented material is being trapped behind the tip.

This slow-release material may suffer some degree of degradation as a result of being held back for prolonged periods at high temperature. There is evidence to suggest that this type of degradation can play a significant role in the performance of the cap in-service, especially when used with pressurised containers, creating potentially weak regions prone to cracking or rupture when stressed.

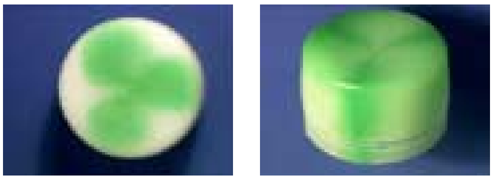

Figure 2 - Mould filling flow front patterns.

NB:

- *MOULD FRONTS* - It is important to recognise that this flow pattern exists in *all* caps produced by this particular hot runner design, irrespective of colour, but the effect is not usually visible because of a lack of colour contrast.
- *COLOUR CHANGE* - On some occasions it was observed that changing the processing settings could produce a cap with a visible difference in colour despite being produced from an identical pigmented feedstock.

Although the DoE run order should ideally be completely randomised to isolate serial effects (e.g. accumulation of slip within mould), some compromise was required to reduce the duration, cost and environmental drift of machine settings in the trials. The following factors were grouped:

- pigment - avoids frequent flushing to purge previous pigment and ensures no residual traces of previous pigment with changes
- replicates - more efficient to produce identical runs consecutively
- mould temperature - difficult to control accurately
- melt temperature - requires long stabilisation time.

MEASUREMENTS

Once moulded, the caps were aged for several weeks to allow them to stabilise prior to measurement. Any changes in the cylindricity of the cap, its overall diameter or the screw thread pitch and depth have the potential to impair the quality of the seal formed between the cap and the bottle, and thus its in-service performance.

In this study the following quantities were chosen to be measured:

- weight
- colour/intensity
- lid surface contours and thickness
- cap perimeter at three distances from the closed face
- screw thread profile.

Thickness

The lid thickness was measured using a flat-faced micrometer at two positions on the cap, away from any raised moulding features, as indicated in Figure 3.

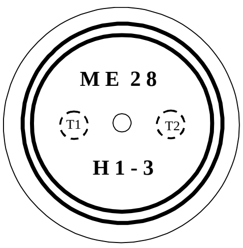

Figure 3 - Thickness measurements, T1 & T2.

Colour

The colour of each cap was determined by measuring the spectral reflectance of the flat surface of the cap using a Spectra Flash 500 spectrophotometer. The spectrophotometer exposes a small area of the cap to a light source with a daylight colour temperature and compares the % reflectance within the visible spectrum (360-750 nm) to that of reference white and black colour tiles.

External Contours

A Zeiss UPMC 550 coordinate measuring machine was used to interrogate the top surface and perimeter of the caps with a resolution of less than 1 µm in three orthogonal axes, using a 4 mm radius spherical ruby probe tip. All caps were oriented identically.

Height measurements of the top surface of the cap were made at 21 pre-specified positions distributed over the planar top surface of the cap, as depicted in Figure 4 (top). This was used to evaluate the contours and thus any distortion of the outer surface of the cap lid.

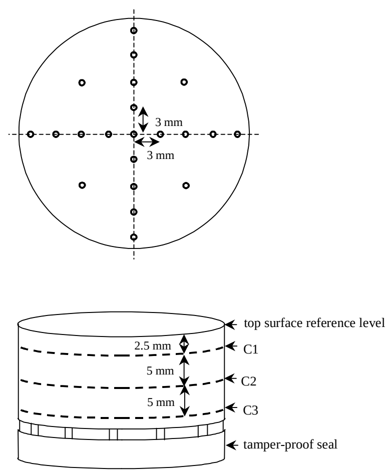

Figure 4 - CMM measurements: (top) flat face and (bottom) perimeter C1 to C3.

Coordinate position measurements over 37 points distributed evenly around the circumference of the cap at a constant height were also made. These circumferential measurements were repeated at three pre-specified heights, as shown in Figure 4 (bottom). This information was used to assess the shrinkage and distortion of the cap diameter with distance from the injection point.

Internal Contours

A UBM laser profilometer with an ADA 3300 sensor unit was used to investigate the threads to a vertical resolution of 1 μm. A duplicate of the internal geometry of the cap was made using a synthetic rubber replicating compound, an example of which is shown in Figure 5 (left), in order to eliminate accessibility problems. Each profile consisted of height measurements with respect to the position along the scan line, distributed evenly over 801 points. These were repeated at three different positions, as shown in the diagram in Figure 5 (right). This information was used to assess the thread dimensions.

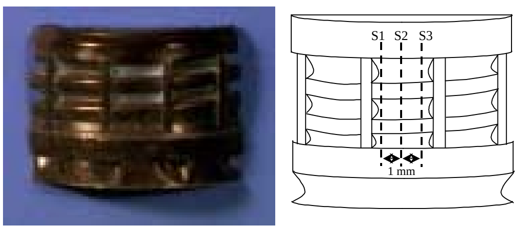

Figure 5 - Thread measurements, S1 to S3.

Some of these data can then be used to calculate additional parameters, such as splay which provides a measure of the parallelism of the cap walls.

DATA ANALYSIS

The profile and coordinate data from all the measurement techniques were initially reduced to a few values describing the main characteristic features of the caps. Subsequently, these quantities were compared and interpreted using:

- analysis of means (ANOM) - used to rank the effect of pigment and processing variables on dimension and appearance measures (e.g. radius, weight or colour)
- analysis of variance (ANOVA) - a statistical technique used to determine the significance of differences between populations and provide a measure of confidence in the trends observed with the means approach.

Analysis of Means

This approach compares the mean measured property values at each level of a processing factor. The effect of injection time, for example, would be determined by dividing the dimension data into three groups representing low, medium and high injection times and evaluating the mean value of data within each group (i.e. the average). This approach only provides qualitative information relating processing variables to changes in dimensional stability. Interactions and statistical significance are obtained by analysing data with statistical methods (DoE and ANOVA).

NB: Care should be taken in examining plots of averaged data for each of the processing factors which can often suggest trends in the data which are not confirmed by the statistical analysis.

Ranking Order

Using the median value of data within each group (i.e. the mid-value of all the data), to rank the effects of processing factors or pigment, limits the influence of outliers or asymmetry in the data. The median is less sensitive to extreme results than the mean and this makes it a better measure than the mean for highly skewed distributions (of which there was widespread evidence here).

NB: As with all statistical measures, both the mean and median values are estimated measures of the location of a population hence rankings based on either are simply guides to assist in the determination of the importance of variables rather than being definitive.

Analysis of Variance

Each of the pigment and processing variables affect the measured data to different degrees. Some have no more influence than might be expected through experimental/random scatter. The variance in the data both within and between populations were analysed to draw conclusions about differences in the group means and the probability that these differences were due to treatment effects. A factor was considered significant if the hypothesis that its effect on the data was attributable to chance could be rejected with at least 95% confidence.

Data Reduction

In order to determine the principal quantities defining the geometry of the cap from the data, some initial analysis was required. This was needed to reduce the information for statistical handling and comparison purposes, without losing valuable range data by averaging.

Flat Lid Surface

A least-squares tensor-product polynomial was fitted to the nominally plane surface of the cap. The flatness of the cap was estimated by determining the maximum orthogonal departure of the actual data from this least-squares plane.

Curved Cap Walls

A least-squares approach was also used to fit a cylinder to the three circumferential passes representing the circular surface of the cap to determine the cap radius. The departure of the actual data from the ideal cylindrical form was then used as a measure of the lack of rotational symmetry of the cap.

The splay was estimated by comparing the changes in diameter of the cylinder which can be fit to the perimeter measurements at three different heights along the cap.

Split Thread Section

Alignment errors in the profilometer data were accounted for by fitting a pair of parallel minimum zone lines to the data. The thread pitch was thus defined as the separation between the two peaks lying on one of the lines and the thread depth was defined as the orthogonal separation between the two lines.

RESULTS

Data Representation

CMM and Profile Data

The geometric data was determined from the CMM external surface coordinates and thread profiles, typical examples of which are shown in Figures 6-8.

Figure 6 shows a bar chart representation of the coordinate sampling of the cap lid, with the zero plane indicating the least squares plane of best fit to the data.

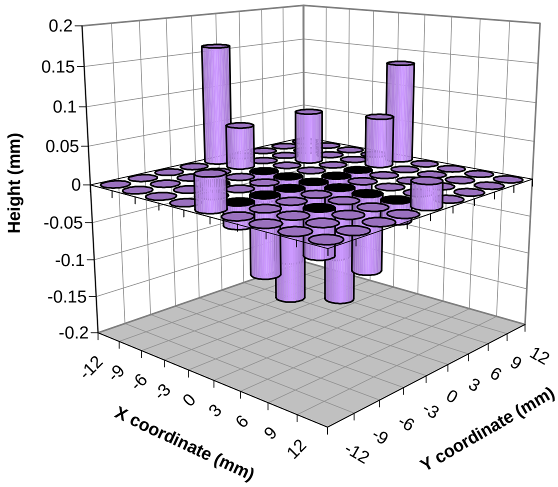

Figure 6 - Cap lid coordinates.

Figure 7 shows the perimeter/circumference coordinate sampling, C1 to C3 as described in Figure 4, with the solid line representing a perfect ∅38 mm circle for comparison.

NB: This data includes an error due to the finite size of the contact probe (∅8 mm), thus coordinates are overestimated by 4 mm in all axes.

Figure 8 shows both typical thread profiles

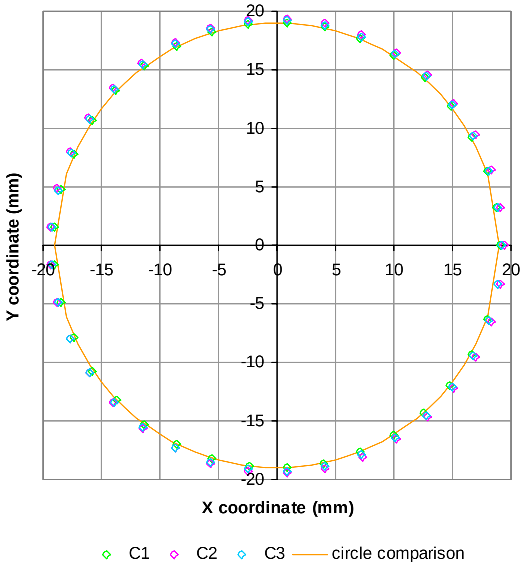

Figure 7 - Cap perimeter coordinates.

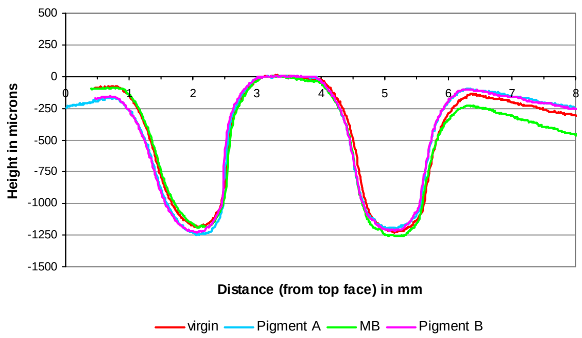

Figure 8 - Raw laser profilometer data for different pigmented feedstocks.

and the effect of pigmentation on the thread for nominally identical processing conditions.

Typical comparative data are shown in Table 4. Here, the mean and standard deviation for the principal measurements from batches of five replicate caps are presented. These batches were produced using identical processing conditions, namely all process variables set to the mid level target value. These data show the low scatter in characteristic quantities for caps produced within a single batch and also the effect of changing pigmentation only on the nature of the cap produced.

Table 4 – Cap Size, Shape and Colour Data

Colour	Pigment A	MB	Pigment B	Virgin
weight (g)	3.053 ± 0.001	3.052 ± 0.001	3.031 ± 0.001	3.040 ± 0.001
thick1 (mm)	1.707 ± 0.002	1.684 ± 0.001	1.689 ± 0.001	1.705 ± 0.003
thick2 (mm)	1.686 ± 0.002	1.664 ± 0.001	1.673 ± 0.003	1.686 ± 0.002
flatness error	0.081 ± 0.008	0.106 ± 0.001	0.111 ± 0.006	0.114 ± 0.002
radius (mm)	19.178 ± 0.001	19.210 ± 0.001	19.142 ± 0.004	19.119 ± 0.001
cylindricity error	2.68 ± 0.02	2.92 ± 0.02	2.54 ± 0.01	2.47 ± 0.02
splay (ratio)	0.9811 ± 0.0001	0.9801 ± 0.0001	0.9818 ± 0.0001	0.9827 ± 0.0001
thread pitch (µm)	3106 ± 26	3065 ± 41	3120 ± 49	3131 ± 23
thread depth (µm)	1212 ± 9	1218 ± 5	1205 ± 5	1208 ± 8
colour peak (% reflectance)	30.86 ± 0.11	26.74 ± 0.33	34.08 ± 0.14	38.22 ± 0.15
colour intensity (greyscale)	48.02 ± 0.08	45.58 ± 0.39	47.63 ± 0.26	63.01 ± 0.13

ANOM Plots

ANOM plots were produced for each of the important cap dimensions which were measured directly or calculated from co-ordinate or profile data. Typical examples are shown in Figures 9 and 10.

In these plots, potential trends or optima can be seen as each process factor changes from low to high setting, as in Figure 9, or the effects of a change in the pigmentation used, as in Figure 10.

In both the ANOM plots filled symbols represent those relationships which are statistically significant (as determined from ANOVA results) and hollow symbols indicate trends which are subject to large scatter and are therefore unproven statistically.

Weight

The cap weight is a measure of the quantity of material injected and retained within the moulding during the processing cycle. Using the cap weight as an example, it is apparent from Figure 9 that hold time, melt temperature and injection pressure have statistically proven influences on the cap weight and of those the hold time has by far the greatest effect. Some of the processing variables show linear relationships e.g. hold time and hold pressure, others show distinct optimum settings within the processing window studied e.g. mould temperature. The global average for the cap weight of all the measured caps is indicated by a dashed line in this plot.

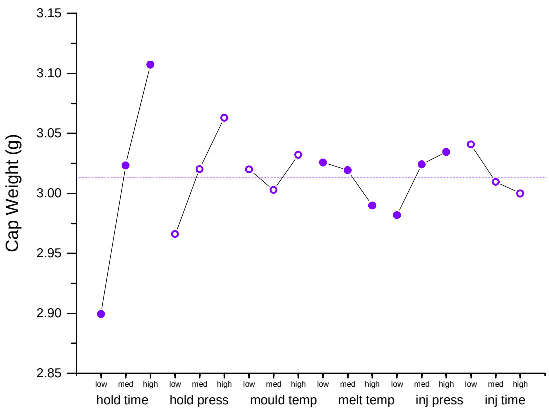

Figure 9 - ANOM plot of influence of process variables on cap weight.

The influence of pigmentation on cap weight is shown in Figure 10. It can be seen that whilst pigment B changes the cap weight by more than the other feedstocks, the differences seen due to different pigments are not supported statistically.

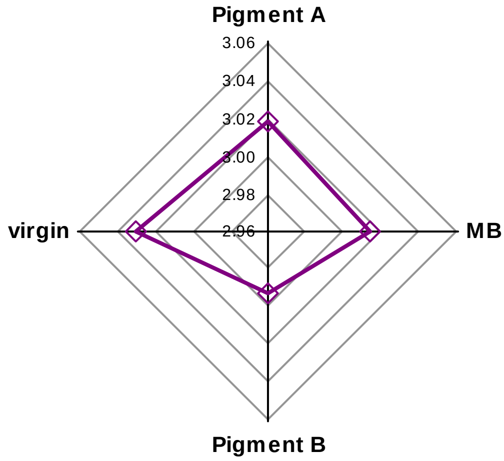

Figure 10 - ANOM plot of influence of pigment type on cap weight (g).

Further to these plots, other relationships can often be determined as shown in Figure 11. Here, as might logically be expected, the almost linear correlation between cap weight and lid thickness is evident.

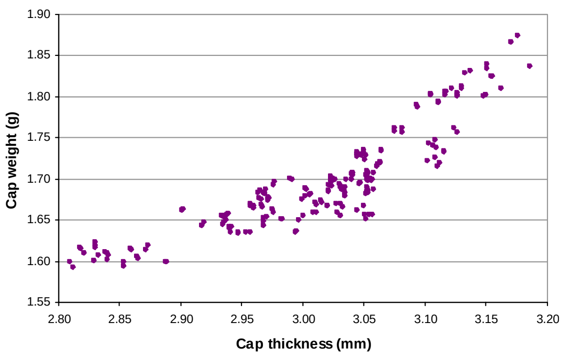

Figure 11 - Plot of weight against thickness for all individual caps.

Appearance

The colour of the cap is a measure of the percentage reflection of different visible wavelengths and is highly dependent on the specific pigment formulation used, shown in Figures 12 and 13.

Figure 12 shows the raw spectral data for each of the green pigments used in the study, from caps produced under identical processing conditions. The reflectance at the peak in the colour spectrum was taken as one measure of appearance and the greyscale level (lightness where black = 0 and white = 100) as another.

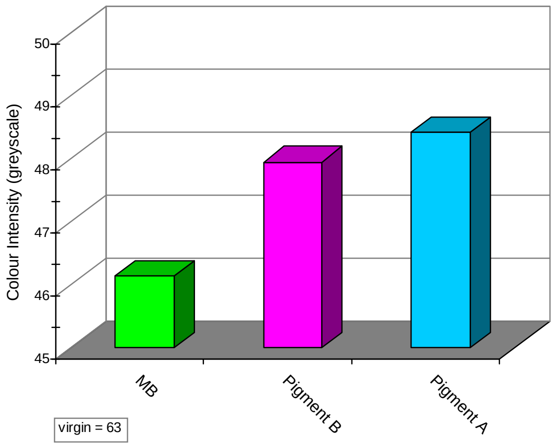

Figure 13 - ANOM plot of influence of pigment on colour intensity (greyscale).

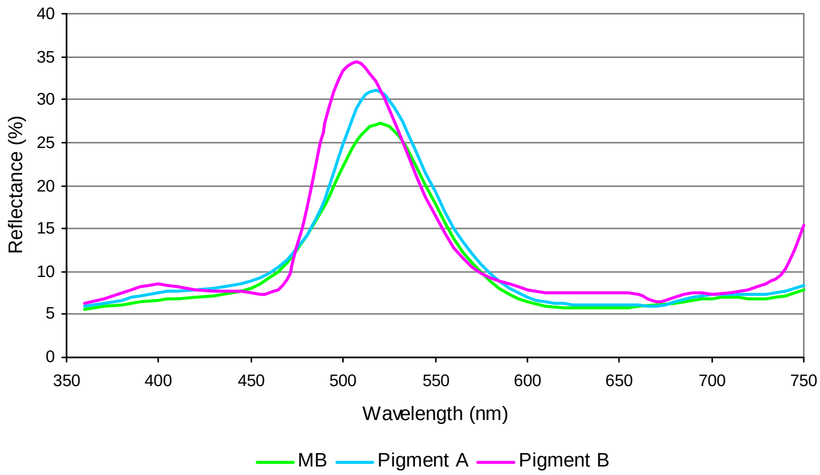

Figure 12 - Typical raw data colour spectra for different green pigments.

More surprisingly, it was found that changing processing conditions also changed the colour of the cap, as highlighted in Figure 14. This has implications when colour-matching new products, pigment formulations or materials to old ones that may require different process settings.

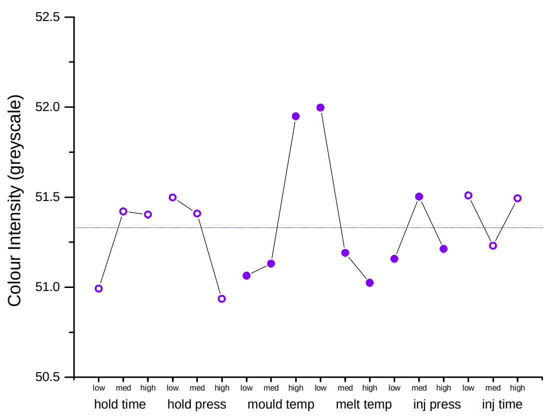

Figure 14 - ANOM plot of influence of process variables on colour intensity.

Radius

Figure 15 shows the changes in the diameter profiles of the cap walls with different pigment formulations. These caps were produced using identical processing conditions, namely all process variables set to the mid level target value.

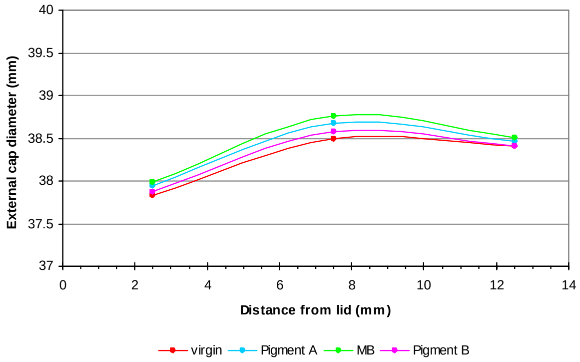

Figure 15 - Curved cap wall profiles for different pigments.

This plot also shows that changing pigment type alone can alter a vital closure dimension, e.g. changing from virgin to MB pigment produces and an overall increase in cap diameter, possibly causing the moulding to fall outside required tolerances.

DoE Results Summary

From the factors considered in this study, the statistically significant factors and interactions influencing the appearance and dimensions of bottle cap mouldings are presented in Table 5 (upper and lower, respectively). The influence on the principal cap dimensions of the individual factors and interactions is summarised.

Table 5 – Statistically Significant Factors (upper) and Interactions (lower)

Parameter	*Pigment*	*Hold Time*	*Hold Press*	*Mould Temp-HS*	*Melt Temp*	*Inj Press*	*Inj Time*
weight		✓			✓	✓	
thick1			✓	✓		✓	
thick2		✓	✓	✓			
flatness error	✓	✓					✓
radius		✓	✓		✓	✓	
cylindricity error		✓					✓
splay		✓					✓
thread pitch					✓		
thread depth		✓				✓	
colour peak	✓	✓		✓			
colour intensity	✓			✓	✓	✓	

Parameter	*pigment × hold press*	*pigment × melt temp*	*pigment × inj press*	*hold press × melt temp*	*melt temp × inj time*	*melt temp × inj press*	*hold press × inj press*	*hold press × inj time*	*mould temp × inj press*
weight									
thick1	✓			✓		✓	✓		
thick2				✓		✓	✓		
flatness error	✓	✓					✓		
radius	✓		✓	✓			✓		
cylindricity error				✓			✓		✓
splay	✓			✓			✓		✓
thread pitch									
thread depth				✓			✓		✓
colour peak		✓	✓			✓			
colour intensity	✓	✓	✓			✓	✓		

Processing Variables

- Hold time - the material solidifies and shrinks causing a pressure drop which is compensated for by more material being pumped into the mould cavity. This reduces shrinkage so longer hold times lead to higher:

⇒ weight
⇒ thickness
⇒ thread depth
⇒ diameter
⇒ improved flatness and cylindricity.

- Hold pressure - displays similar effects to hold time by causing improved mould cavity filling (over-packing can occur at high pressures which may explain some of the non-linear trends observed).

- Mould temperature - changes cooling, solidification and shrinkage rates. Higher mould temperatures delay "freezing-off" and lengthen the mould filling time leading to increased:

⇒ weight
⇒ thickness
⇒ thread pitch and depth
⇒ improved flatness and cylindricity.

- Melt temperature – changes the density of the molten feedstock which can lead to increased shrinkage for higher temperatures and thus reductions in:

⇒ weight
⇒ thickness
⇒ thread depth
⇒ diameter.

- Injection pressure - increases lead to shear heating and melt compression resulting in similar effects on measured parameters as seen with hold pressure.

- Injection time - increases in this factor reduce both shear heating and melt compression and increases the cooling rate within the cavity. This leads to an increase in shrinkage and decreased:

⇒ weight
⇒ thickness
⇒ diameter
⇒ thread depth
⇒ poorer flatness and cylindricity.

The effect of pigment in particular is highlighted in Table 6 (bold text indicates statistical significance) and the impact on the mouldings of the other processing variables are listed in Table 7 (filled symbols represent statisitcally significant relationships, arrows indicate direction of maximum or minimum response and semi-circles indicate a non-linear response). The median values are used here to rank the different factors from high to low based on

Table 6 – Median Rankings of Pigment Influence on Cap Size, Shape and Appearance

	high	**➔**	**➔**	**low**
weight	MB	virgin	Pigment A	Pigment B
thick1	virgin	Pigment A	Pigment B	MB
thick2	virgin	Pigment A	Pigment B	MB
flatness error	**virgin**	**Pigment B**	**MB**	**Pigment A**
radius	MB	Pigment A	Pigment B	virgin
cylindricity error	MB	Pigment A	Pigment B	virgin
splay	virgin	Pigment B	Pigment A	MB
thread pitch	virgin	Pigment B	Pigment A	MB
thread depth	MB	Pigment A	virgin	Pigment B
colour peak	**virgin**	**Pigment B**	**Pigment A**	**MB**
colour intensity	**virgin**	**Pigment A**	**Pigment B**	**MB**

Table 7 – Median Rankings of Process Factor Influences on Cap Size, Shape and Appearance

Parameter	*Hold Time*	*Hold Press*	*Mould Temp-HS*	*Melt Temp*	*Inj Press*	*Inj Time*
weight	⬆ h>m>l	⇧ h>m>l	⇧ h>m>l	⬇ l>m>h	◓ m>h>l	∪ l>h>m
thick1	⇧ h>m>l	⬆ h>m>l	◒ h>l>m	⇩ l>m>h	◓ m>h>l	⇧ h>m>l
thick2	⬆ h>m>l	⬆ h>m>l	◒ h>l>m	⇩ l>m>h	∩ m>h>l	∪ l>h>m
flatness error	⬇ l>m>h	∪ h>l>m	⇩ l>m>h	∪ l>h>m	∪ h>l>m	◒ h>l>m
radius	⬆ h>m>l	⬆ h>m>l	⇩ l>m>h	◓ m>l>h	⬆ h>m>l	⇩ l>m>h
cylindricity error	⬇ l>m>h	∪ l>h>m	∪ l>h>m	∪ h>l>m	∩ m>l>h	⬆ h>m>l
splay	◓ m>h>l	∪ l>h>m	∪ h>l>m	∩ m>l>h	∪ h>l>m	⬆ h>m>l
thread pitch	⇩ l>m>h	⇩ l>m>h	∪ h>l>m	◓ m>h>l	⇧ h>m>l	∩ m>h>l
thread depth	⬆ h>m>l	⇧ h>m>l	∩ m>h>**l**	∪ l>h>m	◓ m>h>l	⇩ l>m>h
colour peak	◓ m>h>l	∩ m>l>h	◒ h>l>m	⇩ l>m>h	⇧ h>m>l	∪ l>h>m
colour intensity	∪ h>l>m	∩ m>l>h	⬆ h>m>l	◒ l>h>m	◓ m>h>l	⇧ h>m>l

their influence on the individual characteristic cap quantities

Interactions

The effects of pigment-based interactions:

- pigment × hold pressure
- pigment × melt temperature
- pigment × injection pressure

are likely to be related to the increase in crystallisation temperature evident with phthalocyanine based pigments.

The effects of injection pressure interactions:

- melt temperature × injection pressure
- hold pressure × injection pressure
- mould temperature × injection pressure

are probably based on the amplification of the shear heating and melt compression effect commonly observed with injection pressure alone. However, interestingly, the injection time based interactions show no statistically significant effects on the mouldings.

This procedure of analysing interactions can often magnify weak, statistically insignificant trends when only single factors are considered.

Pigments

Pigment effects can be summarised by:

- nucleation and higher temperature crystallisation,
  - ⇒ early freeze-off
  - ⇒ processing implications
- anisotropic shrinkage ratio,
  - ⇒ dimensional instability
  - ⇒ distortion/warpage.

Table 8 – Median Rankings of Pigment Influence on Cap Size, Shape and Appearance

high	Hold Time
↓	Melt Temp = Inj Press
↓	Hold Press
low	Mould Temp = Inj Time = Pigment

Similarly, Tables 8 and 9 show more factor and interaction rankings. These are assigned based on the number of cap properties which are significantly influenced by a particular factor or interaction. These help to assign the importance of factors or interactions in terms of the scope rather than scale of their impact on the bottle cap mouldings.

CONCLUDING REMARKS

It is important to understand the dimensional stability of injection-moulded artefacts manufactured from commodity polymers. Allowances can be made for increased shrinkage or anisotropic shrinkage by designing an over-sized or unbalanced dimension mould cavity to accommodate these effects.

Alternatively, controlling shrinkage by changing processing conditions is particularly useful when manufacturing items from differently coloured feedstocks in the same mould cavity, where the different pigments may affect the shrinkage to different extents.

It is clear that there are differences in the size, shape and appearance of complex closures associated with changes in pigmentation and processing variables. These differences are due to changes in:

- the stiffness of the moulding on ejection
- changes in material shrinkage ratio
- degree of material compaction within the mould.

The basic trends in the data are summarised in Figure 16 which show the effect on the principal parameters of *increasing* a particular processing variable.

In summary:

- changing pigments affects product dimensions as well as colour
- changing processing variables affects product appearance as well as dimensions
- longer hold times improve dimensional stability
- changing a processing variable or pigment to control one particular moulding property will simultaneously affect many others.

Table 9 – Median Rankings of Pigment Influence on Cap Size, Shape and Appearance

high	Hold Press × Inj Press
↓	Hold Press × Melt Temp
↓	Hold Press × Pigment = Pigment × Inj Press = Melt Temp × Inj Press
low	Pigment × Melt Temp = Mould Temp × Inj Press

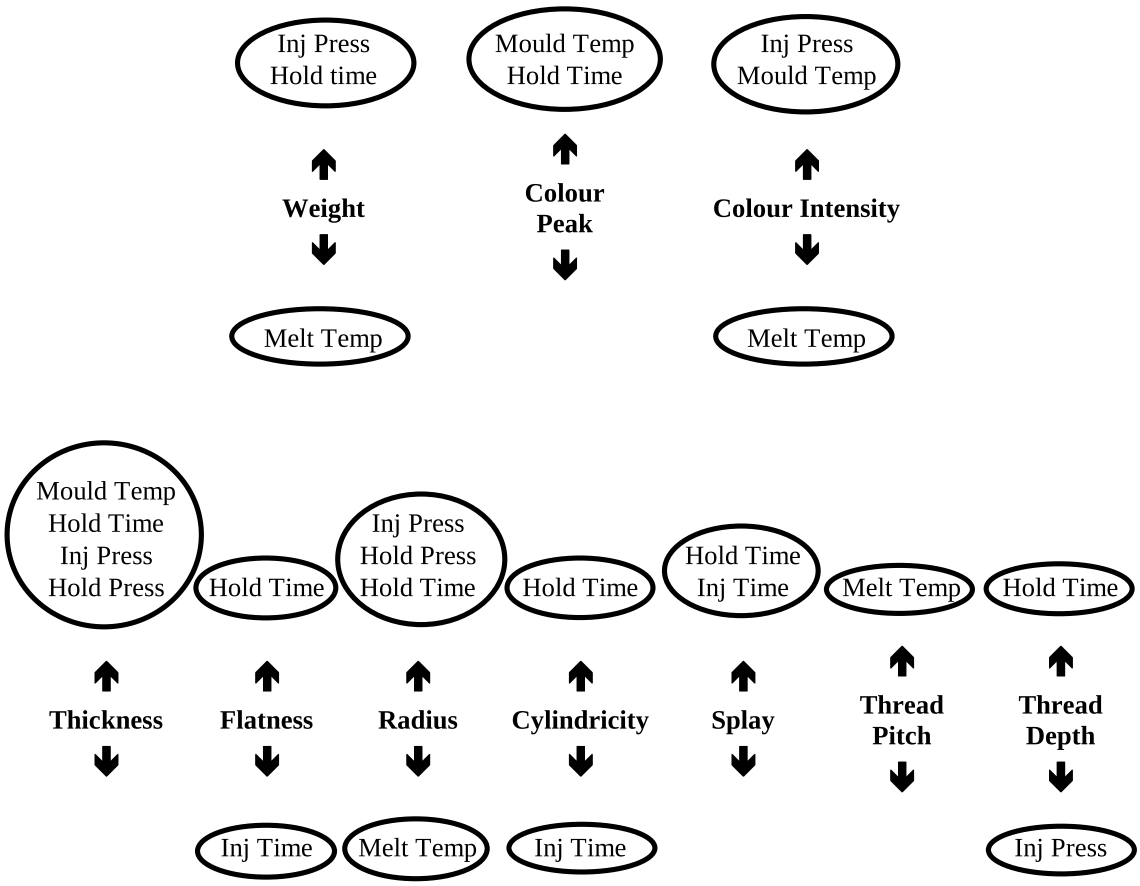

Figure 16 - Control diagram depicting the statistically significant processing variables which affect non-geometric quantities (upper) and geometric quantities (lower).

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Acknowledgements

The research reported in this Measurement Note was carried out by NPL, as part of 'New Materials Work', funded by the Engineering Industries Directorate of the UK Department of Trade and Industry. The authors would like to acknowledge the efforts of colleagues at NPL in performing many of the measurements; Nigel Cross (Centre for Basic Thermal and Length Metrology - CMM), Richard Shaw (Materials Centre) and Peter Clarke (Centre for Optical and Analytical Metrology - colour). In particular, the invaluable contributions of Bernard Butler at Beta Technology (statistical analysis), Georg Rein and colleagues at ColorMatrix (materials/pigments and moulding facilities) and Alcoa (loan of pilot mould tool) are gratefully acknowledged.

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