The Optical Properties of IMD Film

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Abstract: The application of graphics to three dimensional formed products such as mobile phones, car fascias and electronic goods increasingly makes use of in mould decoration (IMD). This allows the graphics to be printed on flat sheets prior to forming. Changes in the visual properties of the printed film occur during forming, often to the detriment of quality of the graphics. In order to distinguish the visual changes from each component, the film must first be studied in isolation. The visual changes can be attributed both to the temperature and strain applied to the film during forming. A study has been undertaken into the suitability of various methods for measuring the optical properties of IMD films. Following on from this an experimental study of the optical properties of IMD films after heating and deformation under controlled conditions has been undertaken. This has highlighted key parameters and mechanisms, which contribute towards these quality failures.

Introduction

In-mould decoration or IMD is a means of decorating a moulded part. Polymer film is decorated with graphics on the front or back surface. It is formed to the required profile and it is then placed in an injection moulding tool. Resin is then injected onto the film resulting in a finished part. This enables 3D graphics parts to be produced during the moulding cycle. Printing on the back, or second surface of the film allows the graphics to be encapsulated between the film and the resin thus protecting the decoration and making it more durable.

There are many markets which currently use or are exploring the use of IMD. Typical applications include mobile telephones, housing, lenses and keypads as well as instrumentation for car fascias, domestic appliances etc.

The current work focuses on the forming stage of the process where the printed film is pressed or drawn into shape. The printed film is subjected to deformation and heating during the forming stage of IMD. It is known that the heat and strain experienced by the film during the process affects the appearance of the graphics in the formed part. However, the mechanisms are not understood and the most appropriate means of identification need to be established.

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In order to establish the effects of heat and strain on printed film the unprinted film must first be analysed so that changes in the printed film may then be ascribed to each component. Thus, the research is aimed towards finding the effect of heat and strain on the optical properties of films used in IMD. The work is also important from the point of view of establishing the suitability of the various methods of measuring the optical properties of printed film.

Films used in the investigation

IMD film is typically based around polycarbonate, which offers mechanical and optical properties desirable for the IMD process. Other polymers, such as polybutyleneterephthalate and polyethyleneterephthalate are blended with polycarbonate to vary the mechanical properties of the film increasing the degree of elongation and lowering the softening temperature. The films were selected in order to permit a study of the differences between pure polycarbonate films and blended films. All the films tested had different surface finishes, which diffused light, affecting the appearance of the finished part.

Four films were compared in the tests, for brevity they are referred to in the paper as follows: “PC”, “PC/PBT”, “PC/PET (50/50)” and “PC/PET (30/70)”. PC is a pure polycarbonate film, PC/PBT a polycarbonate and polybutyleneterephthalate blend, PC/PET (50/50) and PC/PET (30/70) are polycarbonate and polyethyleneterephthalate blends with constituent polymer ratios as stated in parenthesis.

The thickness of the films for the tests was 0.25 mm. With the exception of PC/PBT all films were polished on one side with a matte texture on the reverse. The print is usually applied to the polished side. The PC/PBT film had fine textured and very fine matte surfaces. The very fine matte texture lies somewhere between the polished and matte surfaces and is conventionally the print side.

Methods for measuring the optical properties of IMD film

A range of measurement techniques are available to monitor the optical properties of films. The appearance of a film and second surface print is affected by both the ability of the film to obstruct the passage of light due to its inherent opacity and the ability of the surface to diffuse or reflect incident light. A range of measurement techniques were studied to establish their suitability in evaluating opacity and diffusion/reflection capabilities. The range of parameters investigated and the techniques used are summarised in Table 1.

A detailed description of the principles behind white light interferometry and its uses is given in Lippold. Details on the other measurement methods may be found in Hunt and Field.

Parameter measured	Systems used
Surface roughness	Average surface roughness was measured using a white light interferometer.
Gloss	Percentage gloss was measured using a gloss meter with an illumination/viewing angle of 85°.
Light transmission	Percentage light transmission was measured using a transmission densitometer. Transmission spectra in the 380 to 730 nm range, were measured using a transmission spectrophotometer.
Colour measurement	Transmission CIE L*a*b* values were measured using a transmission spectrophotometer. Reflectance CIE L*a*b* values were measured using both 0°/45° and spherical geometry (specular component included) over both white and black backgrounds.

Table 1. Systems used to measure the optical properties of IMD film

Surface profiling using white light interferometry

Surface roughness measurements were carried out using a WYKO white light interferometer.

Interferometry is a non-contact method of measuring surface roughness and surface form; it will therefore not damage the sample in any way. An interferometer is an instrument that uses the interference of light waves to interpret the surface characteristics of a sample (Lippold).

Average roughness, or Ra, is the arithmetic average of the absolute values of the measured height deviations within the measurement area (Equation 1). These height deviations are measured with respect to a reference mean line that runs centrally through the peaks and valleys. Ra, is expressed in nanometres (nm).

$$Ra = \frac{1}{n}\sum_{i=1}^{n}\left|y_i\right| \qquad (1)$$

with,
Ra: Average surface roughness
|yi|: Absolute value of height deviation

The use of average roughness measurements will tend to average out the effect of atypical peaks or valleys, due to dust on the sample for instance, which will have little effect on the overall value.

The average roughness of the textured surfaces of the films, before heating, ranged from around 1000 nm for the very fine matte side of the PC/PBT to 2300 nm for the fine textured side of the PC/PBT (Table 2).

Percentage gloss

Gloss is a measurement of the directional reflection of light. A gloss meter was used to measure the light reflection characteristics of films. During gloss measurement the surface of the sample is illuminated at a given angle, the light reflected off the sample at the same angle to the plane is collected by a photocell. A diffusing surface will reflect light in all directions resulting in a low gloss level. A perfectly smooth surface will cause all the incident light to be reflected at an angle equal to the angle of incidence resulting in a high level of gloss. A second surface printed sample with a matte surface appears darker than one with a glossy surface. This is due to the matte surface scattering the incident light directly back to the observer. When the scattered light is combined with the light reflected from the coloured area, the object appears lighter.

Gloss measurements were carried out using a Minolta Multi-Gloss 268 gloss meter operating with an illumination/viewing angle of 85° (to the perpendicular of the substrate surface). The angle of 85° was recommended in the instrument manual for low gloss matte surfaces. The instrument is calibrated on a glass standard surface for which the gloss level is 100 %. Measurements were taken over a black background with the rougher surface (fine texture for PC/PBT and matte for other films) facing the light source. For PC/PBT the gloss was also measured on the very fine matte surface.

The gloss level of the films without heating ranged from 5 to 10 % (Table 2) indicating that most of the incident light was diffused by the matte texture.

Percentage light transmitted

The light transmitted through a film sample was measured using a Viptronic Vipdens 620 transmission densitometer. The device works by passing a light beam through a sample into a detector and comparing the light received to that received when no sample is present. The results are presented as a single percentage value of light transmitted through the sample and received by the detector.

The passage of light from the point of source to the measurement device may be obstructed firstly by diffusion as it reaches the film surface and secondly by the opacity of the film itself.

Percentage light transmission was a convenient method of presenting data for non-coated film as provided a single number to characterise light transmission, also it allowed direct comparison with values given on the film supplier's datasheets. Readings were taken both with the rougher surface facing the light source and with the rougher surface facing away from the light source. Readings taken with the rougher surface facing away from the light source tended to have slightly lower transmission values. This was contrary to expectation, as the matte surface will have been expected to diffuse light more effectively before it had the opportunity to penetrate the film rather than after it had passed through the film. The exception was PC/PBT which had a greater light transmission when the fine matte surface was facing the light source, this suggested that the very fine matte texture was a better diffuser of light than the rougher fine texture.

Light transmission through the films without heating ranged from 68 to 76 % for the rougher surface facing the light source (Table 2). When the rougher surface was facing away from the light source the range of values was from 64 to 73 %. A PC film with a polished finish on both sides gave a light transmission value of 90 % indicating that the obstruction of light due to the scattering effect was greater than that due to film opacity.

Film	Average surface roughness (nm)	Percentage gloss at 85°	Percentage light transmission
PC	1236	5.4	68
PC/PBT			65
Fine textured	2250	9.5	
Very fine matte	1040	6.1	
PC/PET (30/70)	1727	7.6	76
PC/PET (50/50)	1797	7.2	76

Table 2. Summary of optical properties of unheated IMD film

A comparison of the properties of roughness, gloss and transmission suggested that there was no straightforward correlation between roughness and gloss or between roughness and light transmission. However light transmission tended to increase as gloss increased.

Transmission spectra

A transmission spectrum shows the amount of light that passes through a film over the range of wavelengths that comprise the visible spectrum. If the spectrum does not show even light transmission through the film at all wavelengths then the hue of a second surface print will appear different from the print side.

Transmission spectra were taken using a Gretag Macbeth transmission spectrophotometer (D_{50} illuminant 2° observer angle). The apparatus measured the proportion of light transmission over a range of wavelengths in the visible spectrum from 380 to 730 nm at 10 nm intervals. The device works by passing a light beam through a sample into a detector and comparing the light received to that received when no sample is present. Light transmission values were outputted as a proportion of the light transmitted through a sample (a transmission value of 1 indicating 100 % light transmission). Again the films were measured at both orientations.

Transmission spectra readings taken for unheated film samples, with the rougher surface facing the light source (Figure 1), showed that light transmission was generally equal across the wavelength range indicating that the films did not possess a transmission bias towards any colour. The blended films, especially PC/PBT showed a slightly reduced transmission in the lower wavelength end of the spectrum. The PC and PC/PET films had a greatly reduced transmission in the lowest part of the visible spectrum between 380 and 400 nm. This suggested the films had UV protection that encroached on a small part of the visible spectrum. The reduced local transmission was not observed in all PC films.

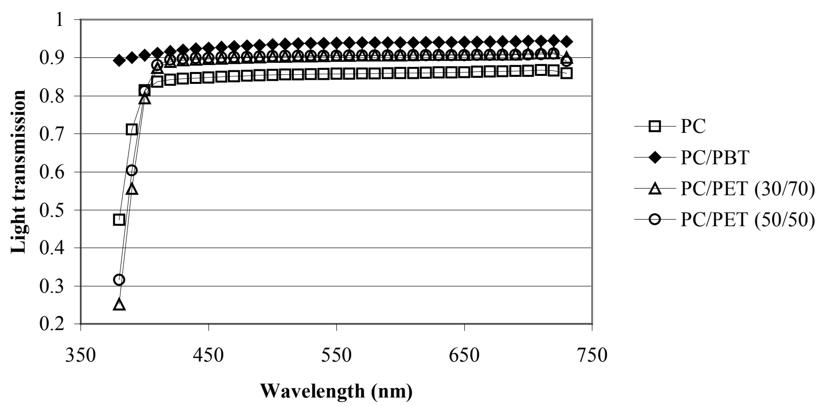

Figure 1. Light transmission spectra for IMD films without heating (rougher surface facing light source)

Transmission spectra readings were sensitive to the orientation of the film. When film samples were measured with the rougher surface facing the light source the transmission values tended to be lower than when the rougher surface was facing away from the light source. Average transmission values (across the spectrum) for PC and PC/PET films were around 0.84 to 0.90 with the rougher surface facing towards the light source, and 0.92 to 0.95 with the rougher surface facing away from the light source. The lower light transmissions observed when the rougher surfaces were facing the light source was due to the light scattering effect of the matte texture diffusing the incident light before it could penetrate the film. A PC film with a polished finish on both sides gave an average transmission value of 0.95, this suggested that measurements taken with a polished surface facing the light source were independent of the texture on the reverse surface. For PC/PBT the average transmission values were 0.86 and 0.93 for readings taken with the light source facing the very fine matte and fine textured surfaces respectively. In contrast to the other films PC/PBT transmitted more light when the rougher surface was facing the light source, further evidence that the very fine matte texture was a better diffuser of light than the rougher fine texture.

This system of measurement provides a great deal more data than transmission densitometry and allows the wavelength, or colour dependency, of light transmission to be established. By measuring the film from both sides an indication of the light scattering effect, distinct from the opacity of the film, may also be established. The transmission values were higher than those recorded with the transmission densitometer. The method is however less convenient than the transmission densitometer, which outputs a single value for light transmission with a higher range of values, which allowed for greater differentiation between films.

Transmission CIE L*a*b* measurement

Transmission CIE L*a*b* values were measured using the transmission spectrophotometer as described previously. The apparatus was capable of measuring film colour without the influence of a background. The operation is the same as spectra measurement with the CIE L*a*b* values being calculated from the transmission spectra. The instrument is calibrated with no sample present. Without the presence of a sample the L*, a and *b* values are 100, 0 and 0 respectively.

For unheated PC and PC/PET films the L* values ranged from 94.2 to 96.9 for the rougher surface facing towards the light source and 98.1 to 98.8 for the rougher surface facing away from the light source (a similar value to PC film with both sides polished). The differences in L* value ranges were due to the scattering effect of the matte surfaces. The PC/PBT film with surface texture applied to both sides gave L* values of 94.6 and 98.8 when the rougher surface was facing away from and towards the light source respectively.

Without heating the transmission a* and b* values of the films, when measured with the rougher surface facing away from the light source, tended to be less than ±0.2 for all films. This indicated that the films possessed no intrinsic colour. The exception was the PC/PBT which had a b^* value of 1.2 which corresponded to the reduced transmission seen in the lower wavelength end of the spectrum. The blue portion of the incident light did not have pass through the film to the measurement aperture as readily and the resulting b^* value was positive as the received light was deficient in blue. For readings taken with the rougher surface facing towards the light source a* values were less than ±0.12 while the b* values were positive and between 0.17 and 0.84. The light scattering by the matte texture influenced the a* and b* values as well as the L* values.

Reflectance L*a*b* measurement

For reflectance colour measurement a light source is focussed onto the sample to be measured. Light reflected by the sample is focussed onto a photodetector and detected at a number of set wavelength intervals throughout the spectrum. The reflectance curve is then used to calculate the CIE L*a*b* colour values. There are two main types of optical configuration used in spectrophotometer measurements namely 0°/45° and spherical. Unlike transmission techniques, reflectance colour measurement requires a background over which the film sample is measured. The measured L*a*b* values for the films will therefore be dependent on the background.

0/45 reflectance spectrophotometer

The sample is illuminated by a beam that is perpendicular its surface and the reflected light collected at 45° to the substrate. The configuration is therefore not capable of measuring directly reflected light. Reflectance CIE L*a*b* values were measured using a Gretag SPM50 0/45 reflectance spectrophotometer (D_{50} illuminant 2° observer).

Spherical reflectance spectrophotometer

For the spherical optical configuration the light source is reflected around a sphere to provide a diffuse light source (a baffle prevents direct illumination of the sample). The reflected light is collected at 8° to the normal and is made up of two components. The diffusely reflected component is composed of light reflected any number of times from the surface of the sphere via the sample. The specular, or gloss component is composed of light directly reflected from the sample via the sphere at –8°. The specular component was included (to exclude the component a light trap is placed at –8° to the normal to prevent direct reflection). Reflectance CIE L*a*b* values were measured using an X-Rite SP68 spherical reflectance spectrophotometer (D65 illuminant 2° observer).

Due to the subjective nature of reflectance measurement of transparent films the stating of L*a*b* values was meaningless unless these values were compared with those of the background. A film may be described in terms of its colour difference, ΔE from the background, this removes the need for background L*a*b* to be stated.

When the rougher surface was facing towards the measurement device the ΔE from the background when using a white background ranged from 7.8 to 9.9 for PC and PC/PET films and 11.0 for PC/PBT when using the 0°/45° spectrophotometer. ΔE ranged from 5.4 to 6.3 for PC and PC/PET films and 4.5 for PC/PBT when using the spherical spectrophotometer. The ΔE from the background when using a black background tended to be higher and ranged from 9.5 to 12.2 for PC and PC/PET films and 17.3 for PC/PBT when using the 0°/45° spectrophotometer. ΔE ranged from 14.2 to 15.7 for PC and PC/PET films and 21.7 for PC/PBT when using the spherical spectrophotometer. The majority of the contribution to ΔE was derived from L* differences.

The effect of film heating on optical properties

Film is heated before and sometimes during the forming process in order for it to be deformed more readily. It is known that the texture diminishes during the forming process. This leads to an increase in glossiness of the formed part, which in many cases is undesirable. The loss in texture could be due to the heat experienced by the film during forming, the strain experienced by the film during forming or the combination of both factors. A series of experiments were carried out to determine the effect of applied temperature and strain on the optical properties of film used in IMD.

The predominant method of film heating in the IMD process is infrared (IR) radiation. A small 500 W ceramic infrared heater was used to heat film samples in the laboratory in order to establish the effect of heating on the appearance of the films. The type of heater was typical of that used industrially, although a bank of lower wattage heaters is usually used in practice. The samples were taped to a frame and heated for 3 minutes by the preheated IR heater. A thermal imaging camera was used to record the surface temperature of film samples that were subjected to infrared heating. The temperatures reached for a given input voltage to the heater were calculated by averaging the surface temperature of the film within the frame boundary. The thermal images showed an uneven temperature distribution with areas above and below the target temperatures.

By varying the input voltage of the IR heater, film samples were heated to average temperatures of approximately 100°C, 150°C and 200°C. The samples were allowed to cool before analysis. The properties listed in Table 1. were measured for the heated samples and compared with those properties for unheated film.

The effect of film heating on average surface roughness, percentage gloss and light transmission are shown in Figures 2, 3 and 4 respectively. None of the films showed significant changes in any of the parameters when heated to 100°C.

The matte side of PC film showed little decrease in surface roughness up to 150°C. When the film was heated to 200°C the film lost nearly all of its original surface roughness. The loss in surface roughness was associated with an increase in gloss level and an increase in the light transmitted through the film to around 90 % (similar to that seen in both sides polished polycarbonate film). PC/PET (30/70) film suffered a significant reduction in surface roughness with increased gloss level and light transmission when heated to 150°C. The changes in PC/PET (50/50) up to 150°C were significant but of a lower magnitude than PC/PET (30/70). Upon heating to 200°C the surface roughness of both PC/PET films fell further and gloss level approached 100 %, indicating complete texture loss. The light transmission for the PC/PET (50/50) reached around 90 % but the light transmission for the PC/PET (30/70) fell between 150°C and 200°C despite the loss in surface texture.

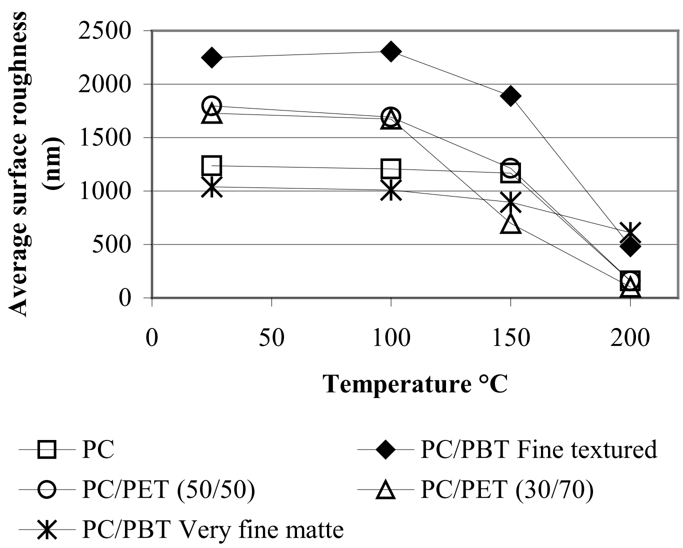

Figure 2. Change in average surface roughness upon heating for IMD film

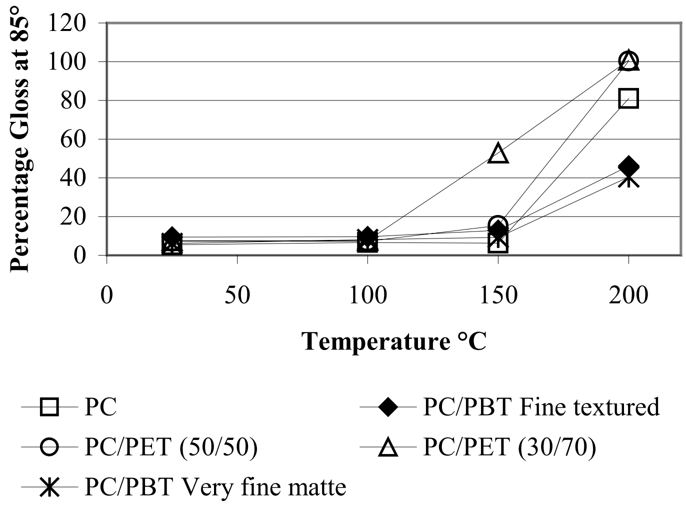

Figure 3. Change in 85° gloss upon heating for IMD film

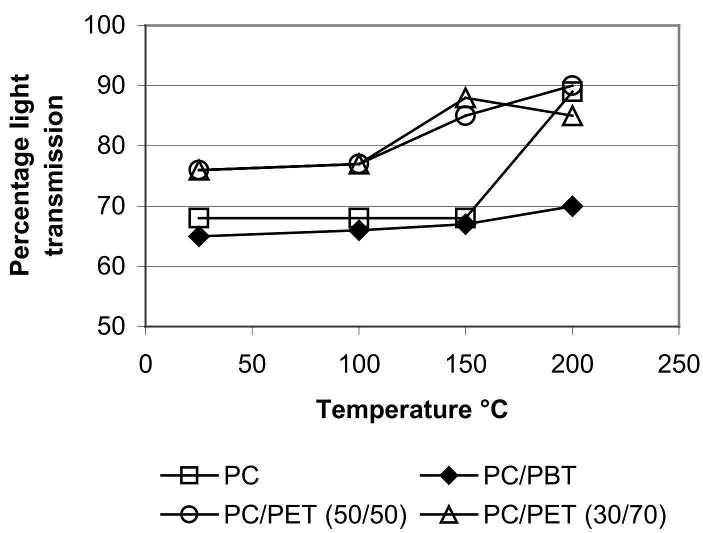

Figure 4. Change in light transmission upon heating for IMD film

The fine textured side of the PC/PBT film suffered a noticeable loss in surface roughness at 150°C. This was accompanied by very small increases in gloss and light transmission. A further reduction in surface roughness occurred when the film was heated to 200°C, this was accompanied by an increase in gloss, which was significant but substantially lower than that seen in the other films, but only a small increase in light transmission. The very fine matte side of the PC/PBT film retained a significant proportion of its original surface roughness when heated to 200°C. The change in gloss level was similar to that of the fine textured side.

The changes in surface roughness, gloss level and light transmission showed similar trends for PC and PC/PET (50/50). Applying heat to the film had the effect of removing the matte texture; this led to a reduction in surface roughness, increased gloss and increased light transmission through the sample. PC/PET (50/50) seemed to have a greater resistance to temperature induced texture loss up to 150°C than PC/PET (30/70) due to the greater proportion of PC making it less soft at high temperatures. For PC/PBT and PC/PET (30/70) films the light transmission was affected by a colour change in the film so that the expected increase due to texture loss was counteracted by the increased opacity of the film itself. This will be explored further later in the paper.

The light transmission spectra for films heated to 200°C (and measured with the rougher surface facing the light source) are given in Figure 5. The corresponding change in transmission L*, a* and b* values with heating are given in Figure 6. Spectra measurements taken with the rougher surface facing towards the light source for PC and PC/PET (50/50) films showed that light transmission increased over the whole of the visible spectrum by a similar amount as a result of heating. There was also an increase in L* value for PC and PC/PET (50/50) films with heating. There was no wavelength related bias in the changes in transmission which was confirmed with no significant change in a* and b*. The increase in light transmission coincided with the loss in surface texture. The PC/PBT showed a reduction in transmission with heating, especially at the lower end of the spectrum. This suggested a colour change apart from that due to lightness which was supported by transmission L*a*b* data. The PC/PET 30/70 film showed increased transmission when heated up to 150°C due to the loss in surface texture. However, when heated further to 200°C the transmission was reduced across the spectrum especially in the lower wavelengths. The reduction in transmission was not as great as with PC/PBT.

The heat related increases in light transmission and L* values observed when measuring with the rougher surface facing the light source were due to changes in the light scattering capabilities of the surface texture. Heating reduced the film texture, the incident light was not scattered so much and therefore a greater amount of light reached the measurement aperture. The change in colour in PC/PBT and PC/PET 30/70 acted as a barrier to light transmission so the light transmitted through the film did not increase as with the other films, despite the reduction in surface texture. The change in colour occurred within the film and was not a surface phenomenon like the texture degradation and was significantly greater in the PC/PBT film than the PC/PET. This suggested that the PBT as an element in a blend was more prone to colour change than the PET.

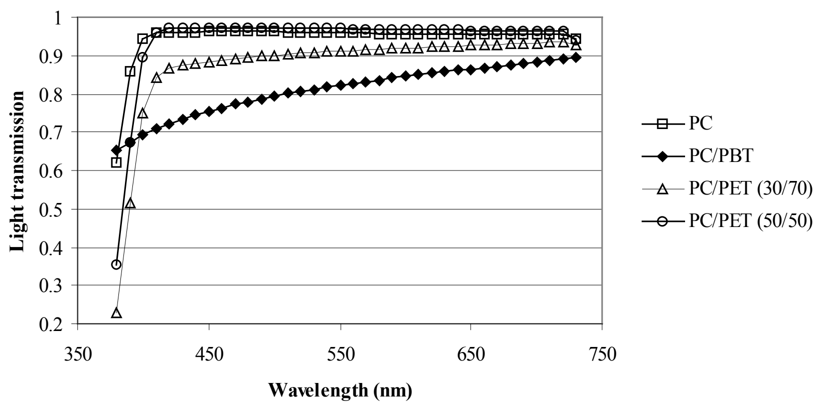

Figure 5. Light transmission spectra for IMD films after heating to 200°C (rougher surface facing light source)

Measurements of PC and PC/PET taken with the matte surface facing away from the light source did not tend to show a change in light transmission due to heat related texture loss in the film. This was because the source light was no longer scattered by the texture before it penetrated the film. These measurements tended to give a better idea of the inherent colour changes in the film as the readings were less affected by light scattering.

When measuring the PC films with a 0°/45° reflectance spectrophotometer the colour difference, ΔE, between the film and background was reduced as temperature was increased. The film L*a*b* values tended towards those of the background. This was due to a reduction in light scattering as the matte surface lost its roughness. This is demonstrated in Figure 7, which shows the change in reflectance 0°/45° ΔE of film from the black background upon heating, with the rougher surface facing the measurement device.

For PC/PBT film the changes in 0°/45° L* value were small compared to those in PC films, this was due in part to the relative reluctance of the texture to deteriorate but was also due to the inherent colour change in the film. The b* values of PC/PBT tended to move away from those of the background as temperature was increased. When measured on a black background there was a change in b* value of around –20 as the film was heated to 200°C suggesting a blue appearance, this was less dramatic on a white background where the change in b* was around + 2 suggesting yellowing.

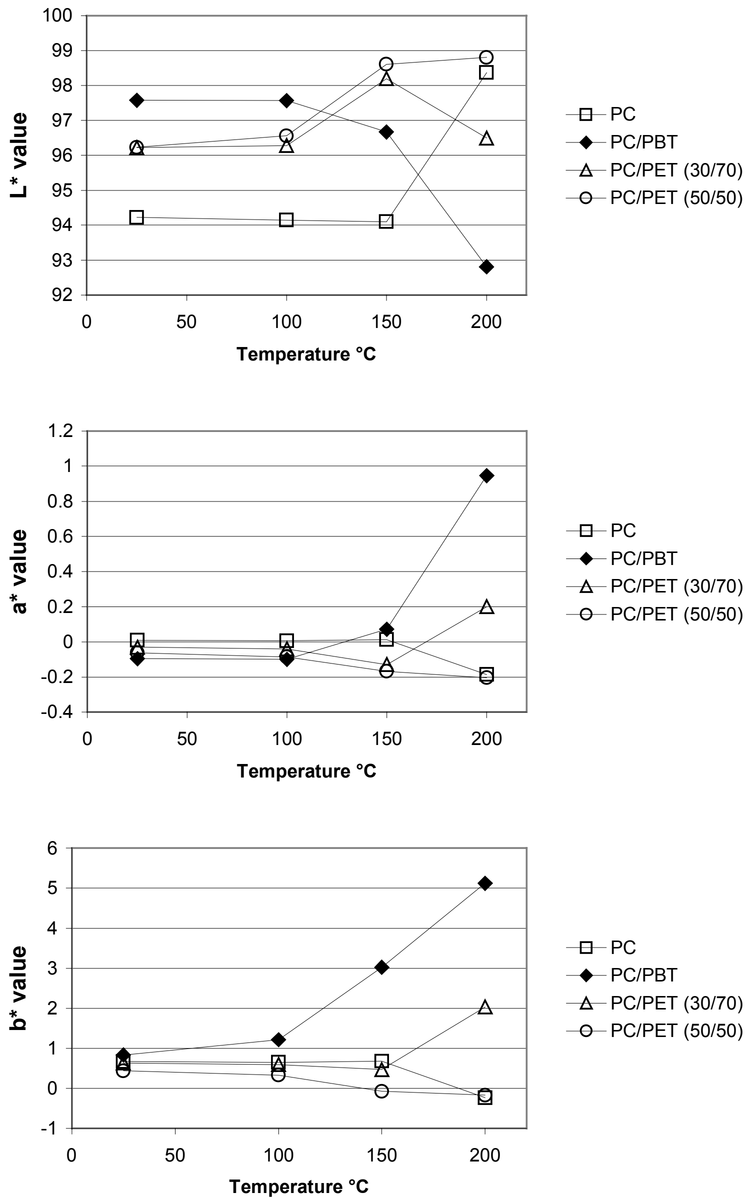

Figure 6. Change in transmission L*, a* and b* values upon heating for IMD film (rougher surface facing light source)

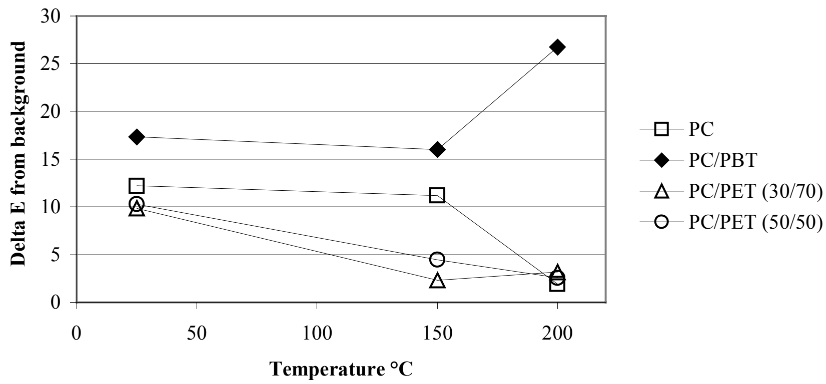

Figure 7. Change in reflectance 0°/45° ΔE of film from black background upon heating (rougher surface facing measurement device)

For PC/PET films the 0°/45° b* values decreased upon heating suggesting the films appeared blue in colour when viewed over a black background. This was more noticeable in PC/PET (30/70) due to the increased proportion of PET in the film. The change in b* value was significantly less than that observed with PC/PBT suggesting that PBT was more susceptible to colour change than PET. When heated between 150°C and 200°C, PC/PET (30/70) did not show any significant change in L* value, the expected increase in L* due to texture loss was counteracted by the colour change in the film. The downward trend in L* value was reversed, as the film became more opaque upon heating.

When measurements were repeated with the rougher surface facing the background, the pattern of change in L*a*b* values was similar. The diffusion occurred in a different location, as light was reflected from the background onto the film.

When using the spherical spectrophotometer there was an increase in L* values over a white background. This was similar in magnitude to those noticed when using the 0/45°. Variation in a* and b* with temperature was smaller than with the 0/45°. Readings taken on a black background showed a slight increase in L* value of PC with temperature and little change in a* and b* values. The PC/PBT showed an increase in L* value with temperature that was significantly higher than for the other films. As with the 0/45° there was a reduction in b* values for blended films when viewed over a black background. Again this was more apparent in PC/PBT then in PC/PET (30/70) due to the higher proportion of PET in the film.

The 0/45° spectrophotometer gave an indication of the change due to the film texture and was a good representation of differences seen by the human eye. The black background appeared dark grey when viewed through the film as reflectance from the background was combined with direct reflectance from the matte surface, however upon heating it appeared black as less diffusion occurred at the first surface. Differences between the trends seen with the 0°/45° and spherical devices were due to the way in which the two instruments illuminated the sample and collected the reflected light. The 0/45 optical configuration illuminates the sample at a single angle and collects at another angle making it highly sensitive to texture variations. When measuring on a textured surface the light was diffused and less of it able to penetrate the film and reach the background. The spherical instrument uses an integrating sphere to diffusely illuminate the sample and collects the light reflected at all angles making it less sensitive to changes in texture. However, the spherical device included a texture dependent specular component.

The intrinsic colour changes (those not due to texture degradation) observed in reflectance measurements of blended films were more evident over a black background than white, evidence that film colour change is subjective depending on the background over which it is viewed. In order to monitor such colour changes in blended film, a black background will offer greater measurement sensitivity. The black background was also more sensitive when measuring changes due to texture loss.

By recording transmission spectra the colour change may be judged without the influence of a background making it easier to anticipate the visual changes when colours other than black or white are used. The transmission spectra data may be used to explain the changes in a* and b* in heated blended film when viewed over a given background. The PC/PBT transmitted less light in the blue end of the spectrum, when viewed on a white background (which should reflect all parts of the spectrum) the film appeared yellow. This was due to the blue component of the incident light not reaching the white background and being reflected back as it was not as readily transmitted through the film. When viewed on a black background, which did not reflect much light, the film appeared blue. This was due to the film reflecting the blue component directly.

The changes seen in the unprinted film may be used to anticipate the visual changes that occur in the printed film. The changes in the appearance in a second surface print will be similar to the changes seen in unprinted film over a background of a similar colour.

Effect of film strain on optical properties

In order to establish the changes in optical properties that occur due to strain, film samples were strained in a tensile tester at ambient temperature. The samples were strained until an area sufficient in size for the purposes of measurement had yielded. The natural draw ratio dictates the elongation that occurs due to yielding under tensile strain and depends on the polymer composition (Roylance). Blended films had higher natural draw ratios than PC film (i.e. strain in the yielded part of the sample was greater in blended films than in PC).

The average surface roughness of film fell with strain as the texture was drawn out. The changes in optical properties with strain were established using transmission techniques (Table 1). The increase in light transmission (measured as an average across the spectrum with the transmission spectrophotometer) for both film orientations upon strain is shown in Figure 8. The increase is expressed as a proportion of the original light transmission.

Upon straining to yield increases in light transmission and transmission L* values were observed regardless of the orientation of the film on the specrophotometer. However, the magnitude of the increase for PC and PC/PET films tended to be greater when the rougher surface of the film was facing the light source due to a reduction in light scattering by the matte surface. When the measurements were taken with the rougher surface facing away from the light source a lesser reduction in transmission occurred, this was due primarily to thinning in the films. This was opposite for PC/PBT as the smoother surface was a better diffuser of light than the rougher surface. No colour change, other than that due to the amount of light transmitted, occurred during ambient strain to yield.

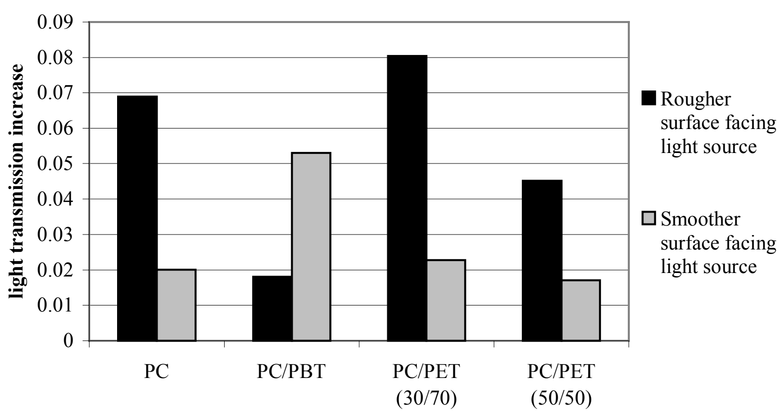

Figure 8. Proportional increase in average light transmission across spectrum due to strain

The draw length and therefore the thinning were greater in blended films. The increased draw length of the blended films gave a greater reduction in average surface roughness after strain, as the texture was been spread over a larger area. The increase in light transmission would be expected to be higher for blended films due to the greater thinning and roughness reduction. However, the relationship between roughness and light transmission is complex. The magnitude of the changes in optical properties that occurred as a result of strain was small compared with the effect of heating to 200°C.

Discussion

The surface texture applied to the films had the effect of diffusing incident light. The ability of the surface texture to diffuse light was not directly linked to the level of roughness. The smoother very fine matte surface of the PC/PBT film was found to be a better diffuser of light than the rougher fine textured surface. However, the heating of the films brought about a deterioration in the surface texture which consequently lead to increased light transmission, increased gloss and a lower reflectance colour difference from the background.

A variety of methods have been used to establish the ability of the films to diffuse or obstruct the passage of light, each of which were found to have advantages and disadvantages. Gloss measurement and surface profiling were the only techniques capable of measuring surface changes independent of film opacity variations. The transmission densitometer was a convenient instrument to use but its readings were influenced by both texture and opacity variation. Transmission spectrophotometry allowed a more thorough analysis of the films permitting an analysis of colour change within the film which could be used to anticipate the appearance of a second surface print. By measuring both sides of a film the levels of opacity and diffusion could be evaluated (provided one side was polished). Reflectance colour measurement was subjective depending on the colour of the background and was also influenced by surface texture and colour changes in the films. The technique would be appropriate for measuring reverse surface print as it would simulate the viewing of an IMD part by the user. The other techniques were more suitable for judging changes in the film in order to anticipate resulting changes in the appearance of a print.

The selection of relevant measurement methods depends on the film. When measuring a blended film, colour measurement was required to monitor intrinsic colour changes. Surface profiling and gloss measurement would then be better indicators of the changes in diffusion properties, as they are not affected by colour change within the film. To measure a polycarbonate film fewer techniques are needed to characterise the film, as an intrinsic colour change does not occur. In this case gloss and transmission densitometer readings are the most convenient means of monitoring changes.

Conclusions

A variety of measurement methods have been used to analyse the optical properties of IMD films and the changes in these properties that occurred due to the application of heat and strain as seen in forming. Visual changes occurred due to the deterioration of surface texture from heat and thinning due to strain. The different measurement techniques had varying sensitivity to the appearance changes. There were also chemical changes in blended films that resulted in an intrinsic colour change and increase in opacity.

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