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Residual stress in polymers—evaluation of measurement techniques

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A comparative assessment has been made of techniques for evaluating residual stress in polymers. Emphasis was placed on the layer removal and hole-drilling methods. A more speculative approach, the chemical probe technique, using the sensitivity of the threshold stress for environment stress cracking to particular chemicals, has been developed to characterize near-surface stresses. Measurements were made for polycarbonate, filled and unfilled acrylo-nitrile butadiene styrene (ABS), and nylon. The materials had been processed by two distinct routes designed to generate different levels of residual stress. The layer removal technique gave the most consistent results for the stress distribution through the thickness but is time-consuming and limited to flat plates. The hole drilling method is potentially more flexible in determining the residual stress in more complex geometries because the measurement is over a small area only. However, although reasonable agreement with the layer removal technique was found for the same principal axis, the values of residual stress calculated for the other principal axis appeared conceptually unreasonable. The chemical probe technique has potential but uncertainty in the quantification of residual stress can arise if significant environment-enhanced relaxation occurs.

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1. Introduction

Residual stresses in a polymer develop in plastic products during their fabrication, for example, from extrusion, blow molding, and injection molding. In injection-molded products, these stresses can be of a magnitude sufficient to induce dimensional and shape changes and, in the presence of specific environments, can result in environment stress cracking (ESC) of the product. The residual stresses may be thermal-elastic stresses, from rapid inhomogeneous cooling of the polymer melt; shear stresses, developed during nonisothermal flow of the polymer melt into the mould; and entropy stresses, from nonequilibrium molecular orientation of the polymer chains [1]. In addition, pressure-induced stresses may develop in injection-molded products upon solidification.

Modeling and measurement of the residual stress distribution as a function of processing variables can provide the tools to develop improved injection moldings and to predict performance. Modeling is currently in progress at C-Mold [2]. Measurement methods are varied and include:

1. bi-refringence measurement
2. layer-removal method
3. hole-drilling method
4. chemical probe technique

The optical polarizability of a polymer chain is anisotropic, that is, the molecular backbone of the polymer has different polarizability in its longitudinal and transverse orientation. This anisotropy is determined by the chemical configuration and conformation of the chain. If the macromolecules are randomly coiled, the anisotropy cancels out on a macroscopic scale. However, residual stress will result in distortion and will induce anisotropy of polarizability, which can then be determined by bi-refringence measurement. The bi-refringence technique has obvious limitations for nontransparent materials, and analysis in terms of residual stress is complicated due to ordering of molecular orientation induced by processing. Accordingly, the main emphasis in this research has been on the other techniques: the layer-removal technique, hole-drilling methods, and the chemical probe technique.

The layer-removal technique [3, 4] is based on measurement of curvature of flat samples following progressive mechanical removal of thin surface layers. In response to removal of a layer, the sample restores equilibrium by warping to a shape that closely resembles a circular arc. The measured curvature as a function of depth removed can be used to calculate the stress distribution through the thickness of the sample prior to layer removal. The technique has been the primary method used for plastics, but the limitation to flat sheets is a

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major constraint as is the inability to assess very near-surface stresses.

Hole drilling is potentially a more flexible method, but while a standard exists [5], there has been no detailed study of its applicability to polymers. The method involves fixing a rosette of strain gauges to the surface of the specimen and then drilling a hole precisely through the center. The strains produced at the surface reflect the stress relaxation that has taken place. Using appropriate models, the measured strains can be used to calculate the stresses for the two principal axes in the plane of the sample.

The chemical probe technique is a more speculative approach and is based on establishing reference data for the relationship between stress and time to crazing and/or cracking for specific polymer-environment combinations. When a plastic with unknown residual stress is exposed for a specific period to an environment, the existence or otherwise of crazing and/or cracking will indicate that the stress is above or below the reference value. This exercise is then repeated for environments of varying aggressivity in a progressive manner to estimate the magnitude of the residual tensile stress. The range of environments is selected according to the accuracy of measurement required. No information about stress distribution is obtained, and the technique is most applicable to plastics with near-surface tensile stresses. The technique is similar in principle to the ASTM method for testing of ABS products [6]. The main distinction is the attempt to establish a quantitative framework.

A comparative assessment of the layer-removal and hole-drilling methods follows, described together with preliminary results from the chemical probe technique.

2. Experimental method

2.1. Materials

The materials used were Polycarbonate from GE Plastics (Lexan 141R), unfilled ABS (Novodur PKT2), filled ABS (Novodur P2HGV) from Bayer, and Nylon 66 (E101L) from DuPont.

2.2. Processing

Flat plates (150 mm × 150 mm × 2.6 mm), were injection molded using a Mannesmann-Demag Kunststofftechnik NC 111 150 tonne injection molding machine. Plates were produced from each material under two sets of processing conditions in order to achieve two levels of residual stress. In the injection molding process, it is very difficult to change one processing parameter without influencing others. Molders often find that many of these parameters are interrelated, and often the optimum conditions for injection moulding are determined after a number of trials. The parameters chosen to change during processing of plates were those that had little or no influence on the other conditions. The processing parameters used in producing plates for all four materials are given in Appendix 1.

2.3. Layer-removal method

2.3.1. Specimen preparation

Using a milling cutter, rectangular specimens (70 mm × 10 mm × 2.6 mm) were removed from the center region of the processed plates perpendicular to the melt flow. The machined edges of the specimen were polished to a 1200 grit finish to minimize any effect of roughness on optical measurement (see later sections).

2.3.2. Specimen thickness measurement

The thickness of the specimen was measured prior to layer removal and after each successive stage of removal. The thickness was determined at four positions along the length of the specimen using a micrometer accurate to 0.001 mm. The mean value was used to define the thickness of the sample. The variation in thickness was usually less than ±1% and never greater than ±2.5%.

2.3.3. Layer removal

Uniform layer removal was achieved using a conventional milling machine with a fly-cutting tool operating at 1600 rpm and a feed rate of 25 mm/min. During milling, the specimen was fixed and held flat by a vacuum table. Compressed air was used for cooling the specimen. Care was taken to ensure that the layers were removed always from the same surface. After removal of a layer, the end of the specimen facing the cutter was changed around to minimize possible variations associated with small differences in specimen thickness along its length.

In anticipation of marked variations in residual stress close to the surface, the thickness of the layer removed was about 0.05 mm for the first two cuts the thickness was then increased to 0.1 mm.

2.3.4. Measurement of curvature

An optical method was used for curvature measurement. The specimen was located on its long edge in a holder attached to a programmable XYZ table with data acquisition facility. The image of the sample was produced on a screen via a camera attached to a microscope. The specimen deflection was measured by following the edge profile and registering the X-Y reading. Measurements were taken at 1 mm intervals along the length of the specimen. Uncertainties associated with edge roughness were minimized by focusing on the edge that had not been milled. Two sets of readings were taken for each stage of layer removal, the second reading being taken after removing the specimen from the holder and setting it back up again.

The radius of curvature was determined by fitting a circular fit through the data points. The curvature is defined as the inverse of the radius of curvature.

2.3.5. Measurement of modulus with position through the thickness

In calculating the distribution of residual stress in polymers by the layer-removal method, account has to be taken of the variation in modulus in the plane of the specimen at different positions through the thickness of the specimen. Accordingly, measurements of modulus were made at different stages of layer removal using a flexural resonance technique.

2.3.6. Time between milling and measurement

The time between milling and measurement needs to be considered because of possible stress relaxation. The time should be relatively short so that only elastic and not visco-elastic relaxation can occur. An elapsed time of 6 mins was chosen. In a study on filled ABS, it was noted that the curvature was very similar whether the elapsed time was 6 minutes or 16 hours.

2.4. Hole-drilling technique

The hole drilling technique is less laborious than the layer removal method. The surface of the specimen was wiped clean. A rosette of three strain gauges was then fixed to the specimen and bonded using cyanoacrylate. The key step was the hole drilling, which must be carried out to a high degree of precision. Spirit levels were used to ensure that the specimen was uniformly horizontal, and the mill was then attached firmly. Centering of the mill was facilitated with an optical microscope. In order to minimize induced pressure and heat during milling, the process was carried out by hand. Care was taken to ensure that the milling proceeded in the vertical plane with minimal side pressure or friction. The process generated a hole which was approximately flat-bottomed.

The first step was to drill through the center of the rosette and the underlying adhesive minimizing penetration of the substrate. The strain was then monitored with the mill just resting on the surface. Holes were drilled in depth increments of about 0.1 mm with a diameter about 1.7 mm. At each depth, the strain measurement was allowed to stabilize (about 3 mins) with the mill in place, and then the measurement was recorded. To check whether stresses were induced by the mill itself, the mill was rotated anti-clockwise in some tests. No effect on the strain was detected.

The surface strains associated with the stress relaxation due to hole drilling diminished with hole depth and became insignificant for depth-to-diameter ratios greater than 0.5.

2.5. Chemical probe method

The chemical probe method was used primarily for unfilled ABS, although reference data were obtained for polycarbonate also. Tests were carried out under constant load and under four-point bend conditions. The test specimens were prepared from the processed plates and conformed to the standard small tensile specimen as specified in ISO 527-2 with an overall length of 75 mm and a gauge length of 30 mm. The width of the gauge section was 5 mm and that of the end sections was 10 mm. For the bend tests, the specimens were 75 mm × 10 mm plates. The sides of the specimens were polished to a 1200 grit finish. The specimens were then annealed at 6 °C below the T_g value for the polymer over a period of two days and slowly cooled to relieve residual stress.

For constant load testing, the specimen was loaded rapidly using hanging weights, and the environment added to the cell within 60 seconds.

For four-point bend tests, the specimens were loaded to the desired displacement in a multispecimen test jig and immersed in the test fluid within 120 s. To ensure consistency in testing, the specimens were stressed with the face in tension being from the same face of the initial plate.

For ABS, the environments were acetic acid at concentrations of 100%, 70%, and 65%, and also white spirit. For polycarbonate, ethanol, and propanol-toluene mixtures (10:1 and 3:1) were used. Analytical reagent grade chemicals were used with the exception of white spirit for which a commercial sample was utilized. To define the threshold stress for cracking for the particular polymer-fluid combination, the specimens were exposed for different applied loads until fracture, up to a time limit of 30 days. The long exposure was for other purposes [7]. The critical data for chemical probe analysis are short term since long-term exposure creates problems due to stress relaxation.

Measurement of the residual stress in the plate samples was made by attaching small cells on the faces at specific locations and exposing for 10 mins.

3. Results and discussion

3.1. Layer removal

An example of the variation in specimen deflection with progressive layer removal is shown for unfilled ABS in Fig. 1. Using standard software, a circle is fitted to each data-set to obtain the radius of curvature Fig. 2. The curvature calculated at each stage of layer removal is shown as a function of distance from the initial surface position in Fig. 3. These data provide the basis for determining the distribution of residual stress using the relationship established by Treuting and Read [4]:

$$\sigma_x(z_1) = \frac{-E}{6(1-\nu)}\left[(z_0+z_1)^2\frac{d\rho}{dz_1}(z_1) + 4(z_1+Z_0)\rho(z_1) - 2\int_{z_1}^{z_0}\rho(z)\,dz\right] \quad (1)$$

where $\sigma_x(z_1)$ is the stress in the longitudinal direction of the specimen at a distance z_1 from the mid-point of the specimen, $E(z_1)$ is the elastic modulus, z is Poisson's ratio, z_0 and z_1 are respectively the distance from mid-point of the specimen to the surface and to the position of the last layer removal, and ρ_x (z_1) is the curvature. The curvature is assumed to be positive when the specimen curves away from the machined surface and negative when it curves towards the machined surface. Equation 1 assumes that stresses are approximately equi-biaxial.

The curvature of the specimens was clearly discernible for all the materials with the exception of the polycarbonate. Very low values of deflection were obtained for polycarbonate samples that were processed by either the EPQ/IIa or EPQ/IIb routes. The implication is that the residual stresses are too small to be detected by this technique.

The in-plane modulus of the specimens at varying distances from the surface for each of the materials is

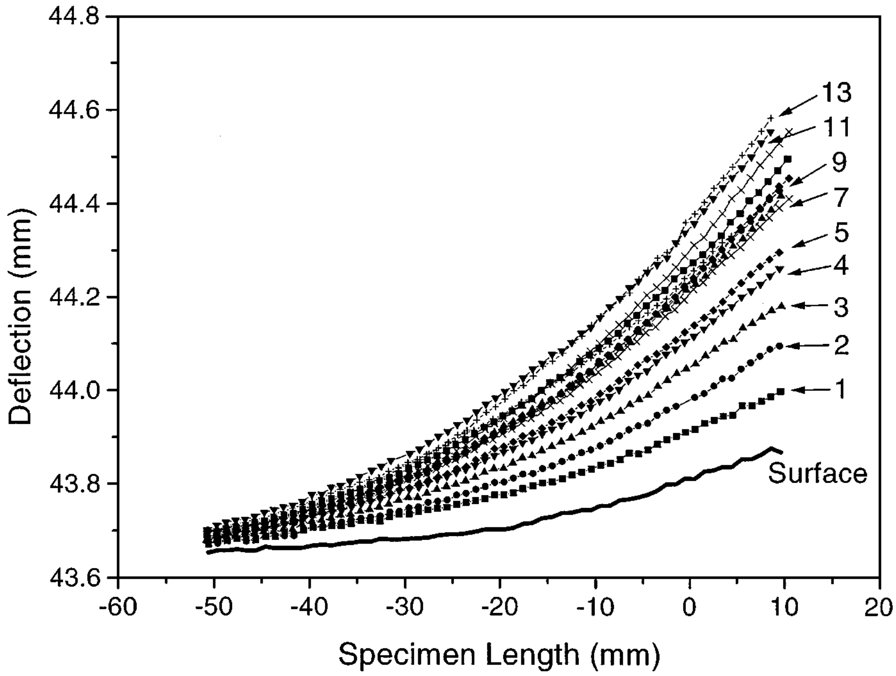

Figure 1 Deflection of a specimen of unfilled ABS during a layer removal experiment.

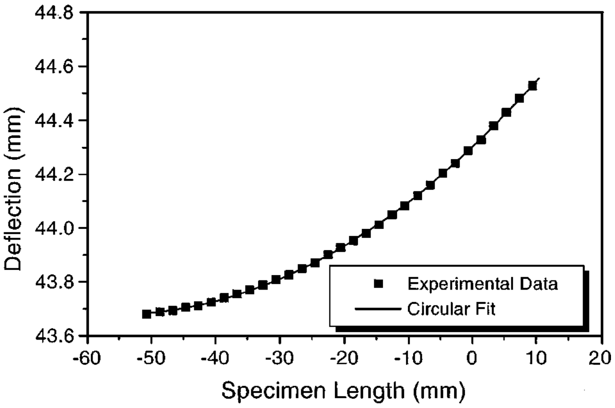

Figure 2 Circular fit used to determine the curvature of an unfilled ABS specimen using the deflection results obtained for layer 13 in Fig. 1.

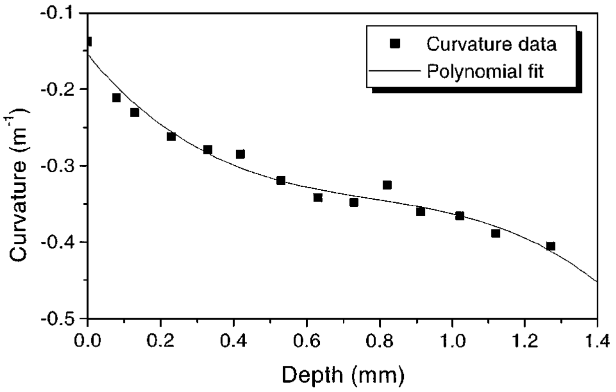

Figure 3 Third order polynomial fit to data for a specimen of unfilled ABS.

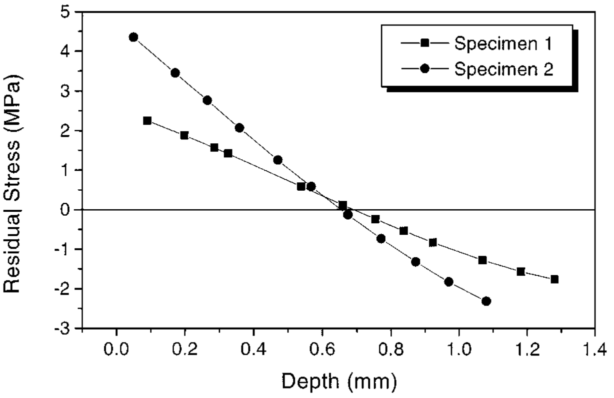

Figure 4 Repeated residual stress measurements in two specimens of filled ABS.

shown in Table I. The modulus is approximately constant through the thickness in each of the materials, with the exception of the filled ABS for which an increase in the modulus was observed towards the center of the specimen. Nevertheless, for analysis, the modulus was assumed to be approximately constant.

The value of Poisson's ratio used was 0.4. This may not be fully representative of the filled material and does not allow also for anisotropy.

Confidence in the measurement process was assessed by measuring the residual stress in two plates of filled ABS that had been produced in the same batch. The measurements were taken from specimens cut from the same position in each plate (Fig. 4). The results indicate that there is a maximum difference of about 1.5 MPa. The key issue is whether the difference is associated

TABLE I Variation of in-plane modulus (GPa) with distance from the surface

Material	Surface	200 μm	400 μm	600 μm	800 μm	1000 μm
PC	2.33	2.30	2.30	2.33	2.33	2.30
ABS	1.94	1.90	1.94	1.91	1.91	1.91
Nylon	1.31	1.31	1.34	1.38	1.38	1.34
Filled ABS	3.86	3.84	3.89	4.07	4.14	4.24

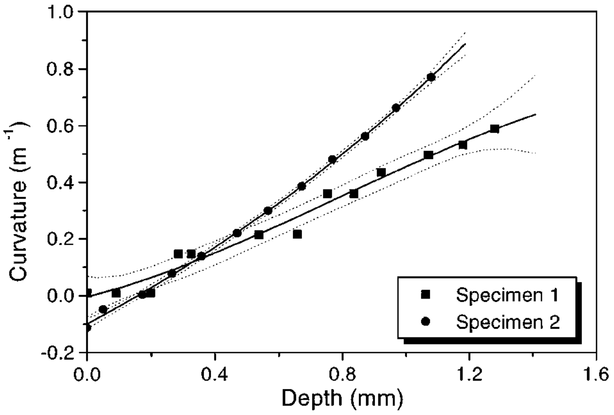

Figure 5 Confidence bands for the polynomial fits to the two filled ABS specimens.

with the measurement technique or with plate-to-plate variations in residual stress. Consistent data were obtained in relation to both the curvature and calculated residual stress at each stage of layer removal in any one data set (i.e., there was not a significant spread in the measurements). Hand calculations were made to check that there was no scaling or calculation errors, which would shift all of the data in a consistent manner. Confidence limits of 95% were then calculated for the polynomial fits (Fig. 5). As the two polynomial curves do not lie within each other's confidence limits, it can be seen that these two curves are statistically different. It would, therefore, appear that the observed differences are due to plate to plate differences in the residual stress rather than measurement variability.

Distributions of residual stresses through samples of ABS (filled and unfilled) and nylon are summarized in Figs 6–8. For unfilled ABS, the stresses were compressive (negative values) at distances between 100 μm and about 300 μm from the surface, with a maximum value of 1.4 MPa, becoming tensile with a maximum value of about 0.5 MPa. The filled ABS showed very contrasting behavior with a tensile region between 100 μm and about 600 μm (maximum 2.5 MPa) transforming to a compressive stress (approaching 1.75 MPa) at greater depths.

For the nylon, the residual stresses were compressive at depths between 100 μm and about 300 μm, with a maximum value of 4.5 MPa, becoming tensile with a maximum value of about 1.5 MPa at greater depths.

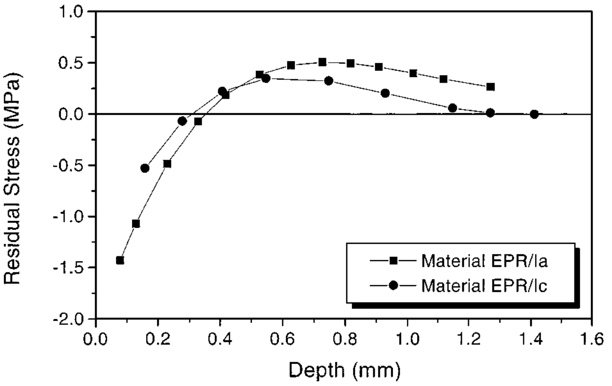

Figure 6 Residual stress in two specimens of unfilled ABS, processed under different conditions and examined using the layer removal technique.

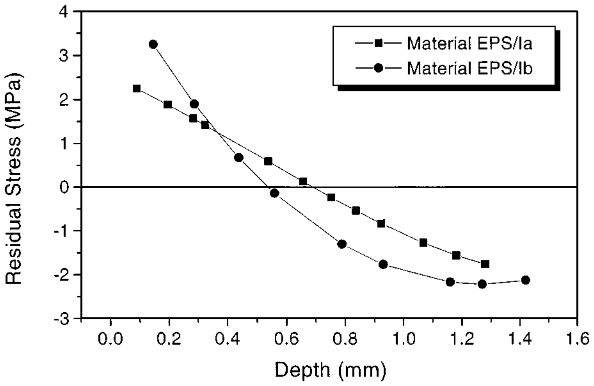

Figure 7 Residual stress in two specimens of filled ABS that had been processed under different conditions and examined using the layer removal technique.

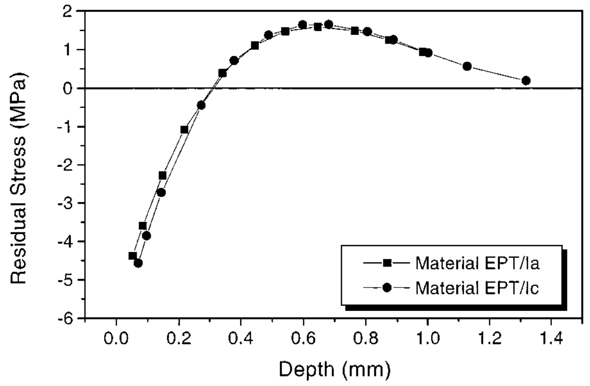

Figure 8 Residual stress in two samples of Nylon processed under similar conditions and examined using the layer removal technique.

The effect of processing route on the residual stress distribution was small and within the sample to sample variability obtained in the repeat tests for the same processing route (Fig. 4).

3.2. Hole-drilling

The derivation of the in-plane stresses is calculated from [8]:

$$\sigma_{\max} = \frac{\varepsilon_1 + \varepsilon_2}{4A} - \frac{\sqrt{2}}{4B}\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2} \quad (2)$$

$$\sigma_{\min} = \frac{\varepsilon_1 + \varepsilon_2}{4A} + \frac{\sqrt{2}}{4B}\sqrt{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2} \quad (3)$$

where $\sigma_{\max}$ and $\sigma_{\min}$ are the maximum (most tensile) and minimum (most compressive) principal stresses present at the hole location before drilling. The values ε_1, ε_2, ε_3 are the relieved strains as measured by the correspondingly numbered, radially orientated strain gauges, where ε_1 and ε_3 are on the two principal axes perpendicular to each other, and ε_2 is at 45° to the two principal axes.

It was necessary to determine the values of the calibration parameters A and B for each polymer at each depth of hole by a separate experiment. An annealed flat strip of the material was prepared, and the hole-drilling

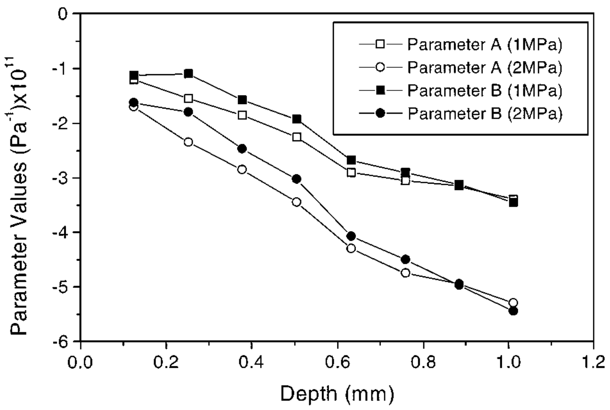

Figure 9 Calibration parameters for unfilled ABS determined at different hole depths by applying known stresses to an annealed sample.

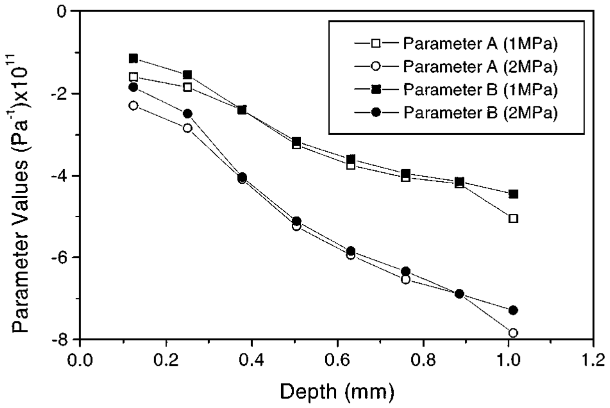

Figure 10 Calibration parameters for Nylon determined for different hole depths by applying known stresses to annealed specimens.

procedure was conducted while it was subjected to a known stress in tension. Tests were carried out for unfilled ABS and for nylon. The values of A and B as a function of depth of hole are shown in Figs 9 and 10. Measurements were carried out at two values of the applied stress in the range of relevance in order to demonstrate consistency of the parameters.

To establish the direction of the stresses, α, the angle between the direction of the maximum residual stress and that of strain gauge 1, was calculated as follows:

$$\tan\alpha = \frac{\varepsilon_1 - 2\varepsilon_2 - \varepsilon_3}{\varepsilon_3 - \varepsilon_1} \tag{4}$$

The following rules apply:

$$\varepsilon_3 > \varepsilon_1 \colon \alpha \text{ refers to } \sigma_{\max}$$

$$\varepsilon_3 < \varepsilon_1 \colon \alpha \text{ refers to } \sigma_{\min}$$

$$\varepsilon_3 = \varepsilon_1 \colon \sigma \text{ refers to } \pm 45\,^{\circ}\mathrm{C}$$

$$\varepsilon_2 < \varepsilon_1 \text{ at } +45^{\circ}$$

$$\varepsilon_2 > \varepsilon_1 \text{ at } -45^{\circ}$$

Using these parameters, the variation of residual stress through the thickness of the material was determined for specimens of unfilled ABS and Nylon (Figs 11 and 12). These values of residual stress were determined from relieved strains that increased from zero up to 600×10^{-6} as the hole was drilled. The maximum stresses related to those stresses that were perpendicular to the flow direction and the minimum stresses to those that were parallel to the flow direction. Tests were conducted on two separate plates at the same location from the gate as in the layer removal technique. The repeat tests gave consistent results for the maximum stress but slightly more variability for the minimum stress.

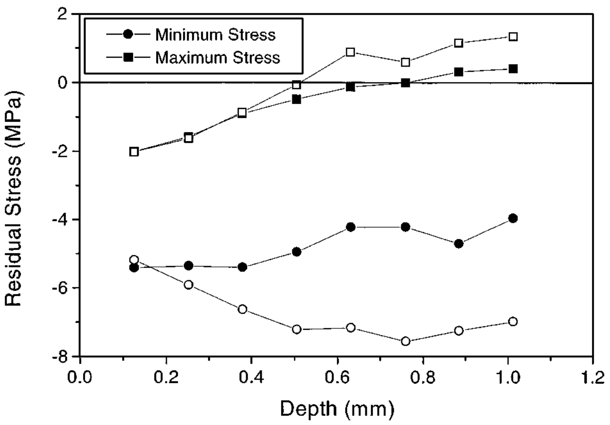

Figure 11 Hole-drilling results obtained along the two principal axes in unfilled ABS. Repeated test results are shown by hollow symbols.

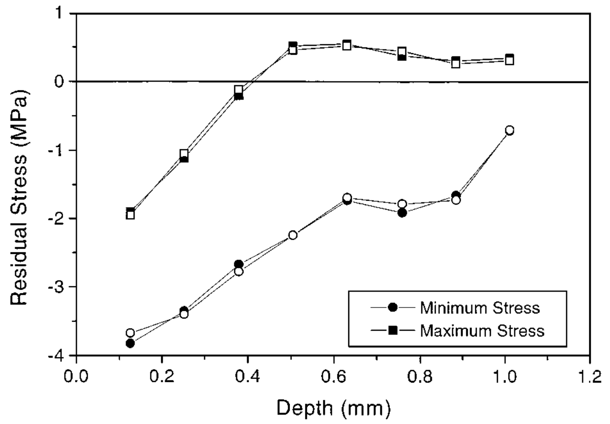

Figure 12 Hole-drilling results obtained along the two principal axes in Nylon. Results from a repeat test are shown by the hollow symbols.

The maximum residual stresses measured using the hole-drilling technique can be compared directly to those obtained from the layer removal technique, as shown in Figs 13 and 14. The agreement was reasonable particularly with regard to the trend. It was not possible to compare the results for the stresses parallel to the flow direction. These were less satisfactory insofar as the stresses determined from hole-drilling were compressive over the full depth of measurement and this would imply a very large tensile stress operating over a small region to balance them. This seemed unlikely and posed some concern for the intrinsic viability of the method. It should be noted that the theoretical basis for analysing the strains in the hole-drilling method does not account for large variations in residual stress over the range of hole depths examined. It is perhaps more applicable to thicker moldings for which the stress gradient is less, although why agreement with the layer

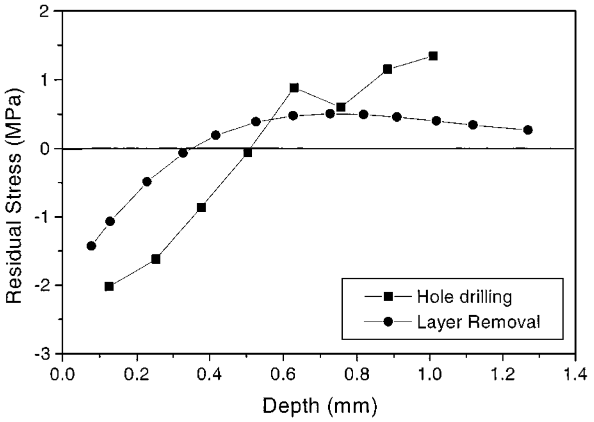

Figure 13 Comparison between the residual stress in unfilled ABS determined by hole-drilling and layer removal.

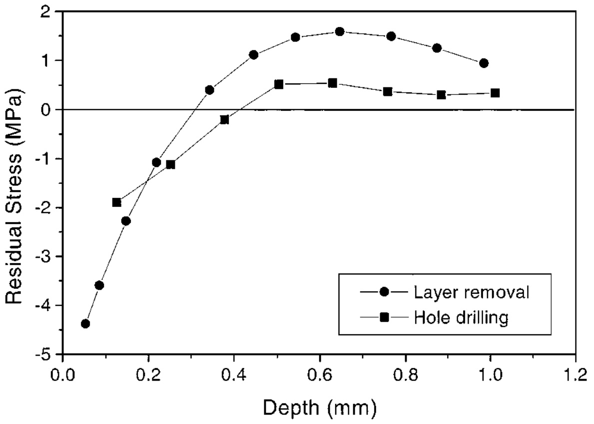

Figure 14 Residual stress determined in samples of nylon using layer removal and hole-drilling techniques.

removal method should be obtained in one principal axis for two different materials is not evident.

Further work using plate samples quenched to generate biaxial stresses will be of value in validating the method.

3.3. Chemical probe

The stress–time-to-craze/crack relationships for annealed polycarbonate and annealed ABS are shown in Figs 15 and 16. A key issue was whether to use constant load or bend data as the reference base for estimating the residual stress in as-processed samples. For polycarbonate, the constant load and 4-pt bend tests gave similar results. However, the results for ABS showed significant disparity because of the marked stress relaxation of this material [7], with the values for constant load being significantly lower. This uncertainty in the reference data poses genuine problems in estimating with confidence the residual stress in an as-processed material. Exposure times need to be relatively short. Also, bend tests may be more representative of the unconstrained test samples.

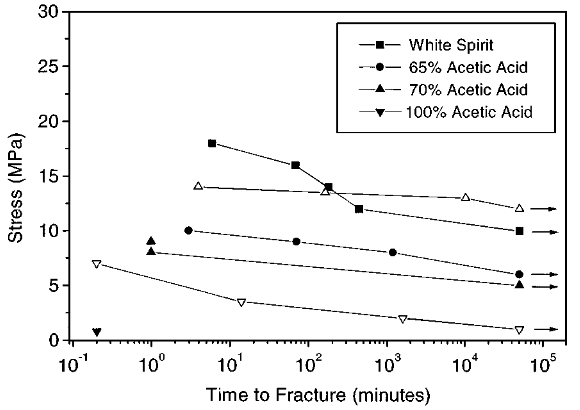

Figure 16 Constant load (solid symbols) and four point bend (hollow symbols) tests applied to annealed unfilled ABS.

The chemical probe technique has been applied to injection molded specimens of polycarbonate and unfilled ABS that had been aged in air for 2, 5, and 20 hours after processing. When the polycarbonate specimens were exposed to a 3:1 propanol: toluene mix, no crazing or fracture was observed in the specimens. Using the four point bend data in Fig. 15 would indicate that the residual stresses are less than 2.5 MPa.

Unfilled ABS specimens aged for 2 and 5 hours fractured in 100% acetic acid but not in 70% acetic. Again, using four point bend data, (Fig. 16) this would indicate that the residual stresses in unfilled ABS are between 3 and 13 MPa. ABS specimens aged for 20 hours did not, however, fail in either the 70% or 100% acetic acid, indicating that the residual stresses in these specimens are below 3 MPa. This decrease in residual stress as the material is aged (Fig. 17) is due to molecular relaxation.

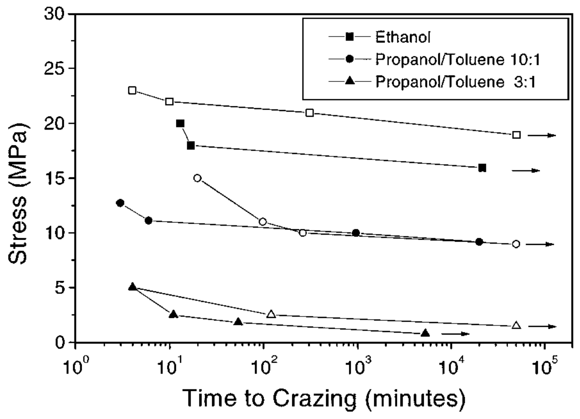

Figure 15 Constant load (solid symbols) and four point bend (hollow symbols) tests applied to annealed polycarbonate.

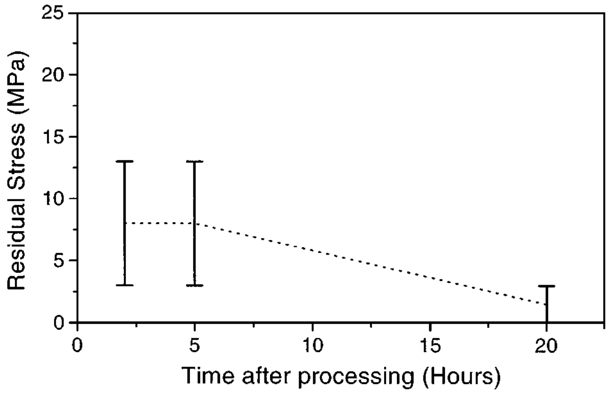

Figure 17 Relaxation residual stresses with time after processing determined using the chemical probe technique.

The chemical probe detects only very near surface stresses that are tensile in nature. The implication of this study is that there is a thin layer ($<50\,\mu$m) of material near the surface in which the residual stress is tensile. The layer removal measurements imply that the residual stress transforms from tensile to compressive over a relatively short distance below the surface. This trend is consistent with modeling predictions for this system [2].

4. Conclusions

The layer removal and hole-drilling techniques gave reasonably consistent results when compared for the same principal axis, perpendicular to the flow direction.

However, the residual stresses estimated by the hole-drilling method in the other principal axis, parallel to the flow direction, were compressive over the full depth of measurement, which seems unreasonable. This may be indicative of a limitation of the analytical approach. Further work to validate the hole-drilling method and to establish its limits of applicability is required.

The chemical probe technique has been shown, in principle, to be a feasible method for determining near-surface residual stresses that the other techniques are not capable of detecting.

Appendix 1

Summary of processing parameters for polycarbonate

Material Code:	EPQ/IIa	EPQ/IIb
Machine Parameters		
Max Machine clamp force:	160 tonne	160 tonne
Max Machine Injection volume:	110 cm^3	110 cm^3
Max Machine Injection pressure:	244 MPa	244 MPa
Max Machine Injection rate:	157 cm^3/s	157 cm^3/s
Process Parameters		
Set barrel temperature:	290 °C	310 °C
Set mold temperature: (coolant temp)	110 °C	110 °C
Coolant flow rate:	11 l/min	11 l/min
Measured melt temperature: (air shot)	225–230 °C	310–330 °C
Measured mold temperature:		
fixed half	108.5 °C	108.5 °C
moving half	108.9 °C	108.9 °C
Fill time:	2.94 sec	2.55 sec
Time for hold pressure:	30.0 sec	30.0 sec

Summary of processing parameters for filled ABS

Material Code:	EPS/Ia	EPS/Ib
Machine Parameters		
Max Machine clamp force:	160 tonne	160 tonne
Max Machine Injection volume:	110 cm^3	110 cm^3
Max Machine Injection pressure:	244 MPa	244 MPa
Max Machine Injection rate:	157 cm^3/s	157 cm^3/s
Process Parameters		
Set barrel temperature:	225 °C	225 °C
Set mold temperature: (coolant temp)	80 °C	60 °C
Coolant flow rate:	11 l/min	11 l/min
Measured melt temperature: (air shot)	225–230 °C	263–268 °C
Measured mold temperature:		
fixed half	79.3 °C	59.8 °C
moving half	78.2 °C	60.3 °
Fill time:	0.88 sec	0.86 sec
Time for hold pressure:	20.0 sec	20.0 sec

Summary of processing parameters for ABS

Material Code:	EPR/Ia	EPR/Ic
Machine Parameters		
Max Machine clamp force:	160 tonne	160 tonne
Max Machine Injection volume:	110 cm^3	110 cm^3
Max Machine Injection pressure:	244 MPa	244 MPa
Max Machine Injection rate:	157 cm^3/s	157 cm^3/s
Process Parameters		
Set barrel temperature:	250 °C	225 °C
Set mold temperature: (coolant temp)	80 °C	80 °C
Coolant flow rate:	11 l/min	11 l/min
Measured melt temperature: (air shot)	256–258 °C	196–198 °C
Measured mold temperature:		
fixed half	77.5 °C	77.4 °C
moving half	77.7 °C	77.7 °C
Fill time:	0.87 sec	5.25 sec
Time for hold pressure:	20.0 sec	20.0 sec

Summary of processing parameters for nylon 66

Material Code:	EPT/Ia	EPT/Ic
Machine Parameters		
Max Machine clamp force:	160 tonne	160 tonne
Max Machine Injection volume:	110 cm^3	110 cm^3
Max Machine Injection pressure:	244 MPa	244 MPa
Max Machine Injection rate:	157 cm^3/s	157 cm^3/s
Process Parameters		
Set barrel temperature:	290 °C	290 °C
Set mold temperature:		
(coolant temp)	55 °C	75 °C
Coolant flow rate:	11 l/min	11 l/min
Measured melt temperature: (air shot)	280–290 °C	286–288 °C
Measured mold temperature:		
fixed half	55–58 °C	71.7 °C
moving half	55–58 °C	72.0 °C
Fill time:	2.25 sec	1.22 sec
Time for hold pressure:	20.0 sec	20.0 sec

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