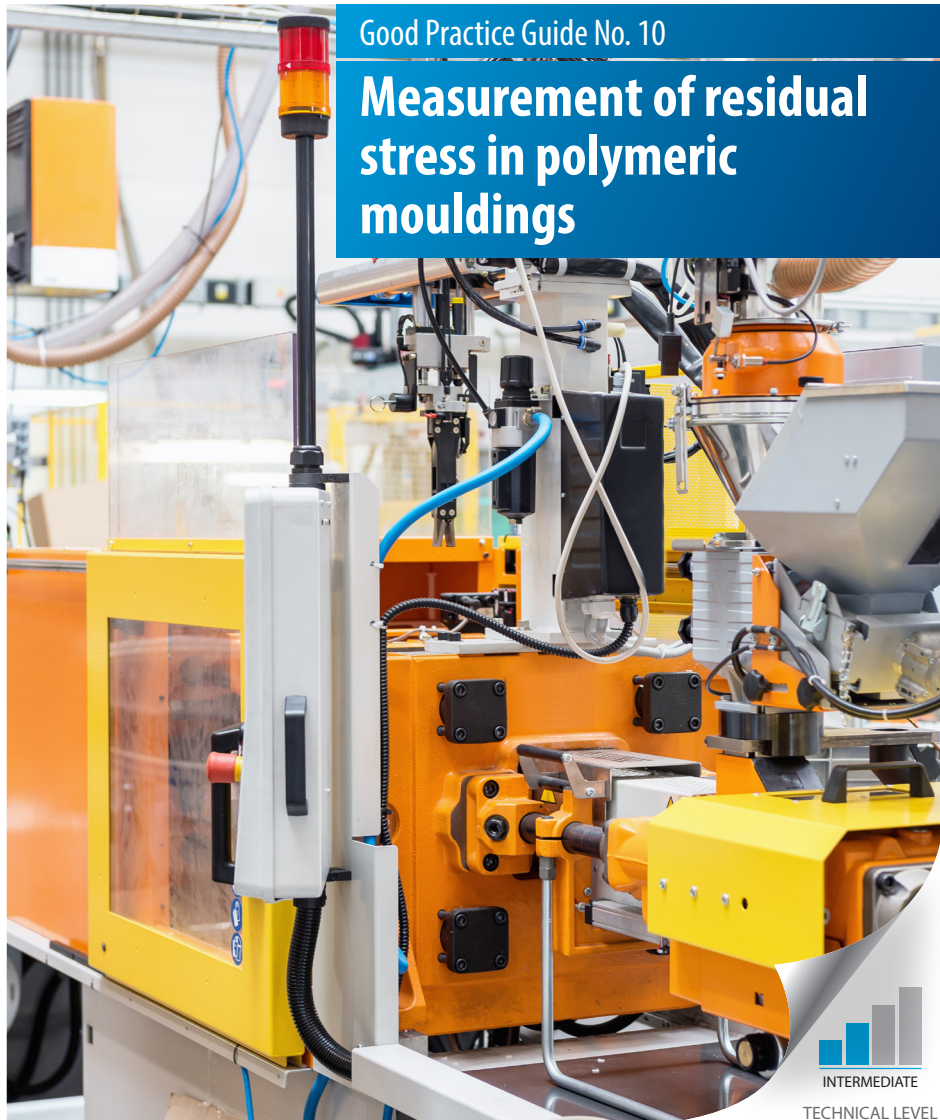


Good Practice Guide No. 10

Measurement of residual stress in polymeric mouldings



INTERMEDIATE

TECHNICAL LEVEL

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NPL Authors and Contributors

Alan Turnbull*

Antony Maxwell*

Sheeba Pillai*

Jim White**

*National Physical Laboratory, Teddington, TW11 0LW

**University of Newcastle, Newcastle upon Tyne, NE1 7RU

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National Physical Laboratory
Hampton Road
Teddington
TW11 0LW
United Kingdom

Telephone: +44 (0)20 8977 3222

e-mail: training@npl.co.uk

www.npl.co.uk

Abstract

Thermoplastic polymer mouldings contain residual stresses that are the consequence of differential cooling rates through the thickness of the mould. Injection moulding, thick-walled blow moulding and profile extrusion can all give rise to residual stress, the magnitude of which will depend on the material, process parameters and process route. Thermoset mouldings may contain residual stress also, as a result of thermal gradients present when curing is completed. Changes in residual stress can occur after moulding as the result of relaxation processes or secondary crystallisation, or as the result of swelling by absorption by water or other molecules with which the moulding comes into contact. Residual stresses cause distortion when out of balance and may influence the fracture behaviour.

This guide describes approaches to measurement of residual stress in polymers using layer removal, hole-drilling and chemical probe techniques. The guide is written in a form similar to most standards documents. It will be of particular value to polymer processors, designers, and materials testers.

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Chapter 1: Introduction

1. Scope

This guide describes approaches to measurement of residual stress in polymers using layer removal, hole-drilling and chemical probe techniques.

- The layer removal method gives information on the through-thickness variation of in-plane residual stress. The measurements are obtained usually in one orientation and repeated with the transverse specimen to quantify the stresses in two dimensions.
- The hole-drilling technique yields information on the through-thickness variation of in-plane residual stress. Results are obtained in two-dimensions. ASTM E 837-20 provides a detailed specification for conducting the measurements. This guide provides only additional information to assist in the application of the technique to polymers
- The chemical probe method gives an indication of the near-surface tensile residual stress in the polymer.

Chapter 2: Layer removal technique

- Principle
- Equipment
- Test specimen
- Procedure
- Analysis and report

2. Layer removal technique

2.1 Principle

When layers are removed from one side of a flat moulding which contains initially a symmetric distribution of stresses, the stresses become imbalanced and the moulding bends. The curvature depends on the stress present in the layer removed and on the elastic properties of the remainder of the moulding. From a series of measurements of the curvature for successive layer removals the distribution of stress in the original moulding can be deduced. The technique is applicable to plate samples. Stresses at the surface and very near-surface cannot be measured by this technique.

2.2 Equipment

- 2.2.1 A conventional milling machine to remove uniform layers using a single-point cutter and fly-cutting action.
- 2.2.2 An optical microscope with a XYZ mounting table.
- 2.2.3 A low-powered laser.

2.3 Test specimen

- 2.3.1 The test specimen shall be in the form of parallel-faced sections cut from sheet or from moulded components. If the test piece is not flat it is still suitable for testing as long as it can be flattened without damage; it should return to the original curvature after flattening if released without removing a layer.
- 2.3.2 The specimen shall be at least 70 mm long.
- 2.3.3 The width of the specimen should be 10 mm.
- 2.3.4 The thickness of the specimen shall be measured to ± 0.005 mm using a calibrated 0-25 mm micrometer.
- 2.3.5 Measurement of thickness shall be made at four locations: ± 10 mm and ± 30 mm along the major axis from the centre of the specimen.
- 2.3.6 The procedure of 2.3.4 shall be repeated each time a layer is removed.

2.4 Measurement of curvature

- 2.4.1 The curvature of the test specimen can be measured by a variety of methods including optical microscopy, laser light deflection or profilometry provided that the technique has the appropriate resolution and range. Although profilometry has the necessary resolution the extent of curvature can exceed the measurement range for some instruments. The laser light deflection technique is more limited than the optical methods in that deflection is measured at essentially one location.
- 2.4.2 The temperature shall be maintained at $23 \pm 2^{\circ}\text{C}$

2.4.2 Optical microscopy

- 2.4.2.1 The edges of the specimen shall be polished to remove roughness associated with machining, enabling more precise definition of the specimen edge. Heating of the specimen shall be avoided and debris shall be removed using a wetted tissue or similar.
- Note. A 1200 grit finish is recommended.
- 2.4.2.2 The specimen shall be held, edge uppermost, at one end, in a suitable frame (Figure 1) and mounted in such a way as to ensure that the sample is placed back in the same position with the same elevation.
- Note. A XYZ table provides a suitable base.
- 2.4.2.3 The microscope is focused on one edge of the specimen. A magnification of $\times 100$ is sufficient for most applications. To minimise errors due to surface roughness, the edge examined shall be that which has not undergone layer removal. Using the X-Y stage, the specimen is moved and the X-Y position of the edge measured at intervals of 1 mm along the length of the specimen.
- Note. Viewing the sample on a screen via a camera attached to the microscope can ease the process of measurement.
- 2.4.2.4 Upon completion of the measurement, the specimen shall be removed, remounted and the process repeated.
- 2.4.2.5 Plot the measured deflection of the specimen with position along the specimen as shown in Figure 2.
- 2.4.2.6 Using standard software, the radius of curvature shall be determined by obtaining the best-fit circle through the data points.
- Note. The curvature is the inverse of the radius of curvature.

- 2.4.2.7 If non-uniformity in curvature exists, a fit may be made to segments of the deflection profile and the curvature of each segment determined.

Note. Specimens cut with the longitudinal direction parallel to the melt flow may exhibit this behaviour.

- 2.4.2.8 The curvature of the specimen is evaluated for each layer of material removed.

2.4.3 Laser-deflection

- 2.4.3.1 The laser shall be mounted on a bench so that it can be rotated in a horizontal plane about a fixed pivot point on its axis. The layout of the apparatus is illustrated schematically in Figure. 3. A clamp to hold the test specimen shall be placed in front of the laser at one meter or more from the pivot point. The clamp shall make line contact on both sides of the centre of the specimen and the specimen shall be secured to it by light springs or by lightly tightened bolts. The specimen shall be mounted with its major axis horizontal and perpendicular to the laser beam. A graduated mm scale with a hole for the laser beam to pass through shall be placed facing the specimen.

- 2.4.3.2 The distance from the laser pivot to the front surface of the specimen and from the front surface to the graduated scale shall be measured before and after each set of curvature measurements. If the apparatus is kept permanently assembled this can be done at intervals of one week.

- 2.4.3.3 Two thin slivers of glass approximately 2 mm wide and 5-15 mm long shall be prepared.

Note. These can be prepared from a microscope cover slide for example.

- 2.4.3.4 The mid-point of the specimen shall be determined to ± 1 mm and marked with a thin line perpendicular to the major axis.

- 2.4.3.5 Thin lines shall be marked perpendicular to the major axis at 30 ± 0.2 mm on either side of the centre line at M1 and M2 respectively (Figure 3).

Note. These lines should be drawn on the face of the specimen not subject to layer removal.

- 2.4.3.6 The glass slivers shall be placed over these off-centre lines.

Note. A smear of water is usually adequate to provide the necessary adhesion.

- 2.4.3.7 The laser beam shall be directed at the line at position M1 and the position of the reflection on the graduated scale recorded; the reading (x_1) is taken to be positive if it falls on the same side of the centre-line as M1.
- 2.4.3.8 The laser beam shall be directed at the line at position M2 and the position of the reflection on the graduated scale recorded; the reading (x_2) is taken to be positive if it falls on the same side of the centre-line as M2.
- 2.4.3.9 The test specimen is then removed and rotated 180° about the axis defined by the laser pivot and the clamp. Steps 2.4.3.7 and 2.4.3.8 are then repeated to give a new set of readings, x_3 and x_4 .
- 2.4.3.10 Calculate the average, x_m from $(x_1 + x_2 + x_3 + x_4)/4$ and obtain the curvature of the specimen (ρ) from

$$\rho = [A(x_m - a) - Ba]/2BAa \quad (1)$$

where A is the distance between laser and specimen, B is the distance between screen and specimen, and a is the distance from the mid-point to M1 and to M2.

2.5 Machining away of layers

- 2.5.1 The machine shall be set for milling with a single point cutter and fly-cutting action.
- 2.5.2 The machine speed shall be 2000 ± 500 revs min⁻¹.
- 2.5.3 The specimen shall be fixed on the machine bed and held flat using a vacuum table/chuck.
- 2.5.4 The height of the specimen shall be adjusted so that the plane of motion of the tool coincides with the upper surface of the specimen.
- Note. The tool is brought into contact with the specimen, without pressure. The dial indicator is then zeroed.
- 2.5.5 The machine bed shall be raised a distance equal to the target cutting increment. An increment of 0.1 mm shall be used.
- Note. Increments other than 0.1 mm may be used by agreement of relevant parties.
- 2.5.6 The test specimen shall be advanced past the rotating tool at a speed of 25 mm/min. Compressed air may be used to minimise heating of the specimen.
- 2.5.7 After each layer removal the specimen shall be released and the thickness measured as described in 2.3.4.

- 2.5.8 The curvature shall be measured as in 2.4.2 or 2.4.3. The elapsed time between milling and commencement of curvature measurement shall be less than 15 mins.
- 2.5.9 The specimen shall be returned to the milling machine and steps 2.5.4 to 2.5.8 repeated until the specimen is reduced to half of its initial thickness or until the specimen stiffness is too small to permit consistent curvature measurements.

Note. If less than half the thickness has been removed only a partial stress distribution analysis can be made; i.e. the residual stress only up to the thickness removed can be determined.

2.6 Analysis of results

- 2.6.1 Plot the curvature versus thickness of material removed (z_0 - z_1 as shown in Figure 4) and obtain a polynomial fit as exemplified for acrylonitrile-butadiene-styrene (ABS) for in Figure 5.

Note. If there is curvature of the specimen prior to layer removal this curvature is subtracted from all measured curvatures. Thus, at the initial surface, the adjusted ρ will be zero. This is most effectively carried out after obtaining a polynomial fit to the data.

- 2.6.2 The residual stress through the thickness shall be calculated using the relationship:

$$\rho = [A(\sigma_m - a) - Ba]/2BAa \quad (2)$$

where $\sigma_x(z_1)$ is the stress at a distance z_1 from the mid-point of the specimen, E is the elastic modulus, ν is Poisson's ratio, z_0 and z_1 are respectively the distance from the mid-point of the specimen to the surface and to the position of the last layer removal (Figure 4).

Note 1. In applying this equation, it is assumed that the stresses are approximately equi-biaxial. This can be verified by testing in two orientations. For other conditions, see Refs. 1 and 2.

- 2.6.3 The modulus of the material shall be measured at each stage of layer removal as it may vary through the thickness.

Note. If significant variation in modulus through the thickness does occur, the applicability of equation (2) can be uncertain.

- 2.6.4 Tabulate values of $\rho(z_1)$ at regular intervals of z_1 using the polynomial fit.
- 2.6.5 Calculate the gradient of the curvature versus z_1 by differentiating the polynomial and tabulate the values.

- 2.6.6 Integrate the polynomial between z_1 and z_0 and tabulate. This gives the integral term in equation (1).
- 2.6.7 Use the tabulated data to calculate $\sigma_x(z_1)$ using equation (2) and plot as a function of depth as illustrated in Figure 6.

2.7 Test report

The test report shall include the following information:

- (a) full description of the material from which the specimens were taken including the processing history;
- (b) description of the form of the material and the location from which specimens were removed;
- (c) elapsed time and storage conditions after processing;
- (d) description of the layer removal process and machining parameters;
- (e) description of curvature measurement method, and elapsed time following layer removal;
- (f) plot of curvature versus thickness of material after layer removal (or of depth of material removed) and typical "best-fit" circle;
- (g) analytical procedure for determining residual stress;
- (h) residual stress variation through the thickness of the specimen with statement of uncertainty.

Chapter 3: Hole drilling method

- Principle
- Normative references
- Equipment
- Test specimen
- Procedure
- Analysis of results
- Test report

3. Hole drilling method

3.1 Principle

The strain at the surface of a polymer containing residual stress will be relieved when a hole is drilled locally. A three-element strain-gauge rosette is adhered to the polymer surface and the relieved strains are measured as a hole is drilled to varying depths through the centre of the rosette. The measured strains can be related to the residual stresses in the polymer at depths up to half the diameter of the hole. However, stresses very close to the surface are not accessible by this method. The technique is applicable to specimens of various geometries provided the area to be examined is flat. In the analysis, the approximation is made that the residual stresses are uniform throughout the drilling depth or essentially so, ie the stress gradient is small in the range of depths of measurement. The technique would not be a first choice for plastics because of possible steep stress gradients, particularly in sheets of a few mm thick. Nevertheless, reasonable agreement has been found with the residual stress distribution determined using the layer removal technique³, although the comparison was made for one principle axis only.

3.2 Normative references

The following standard provides useful background for conducting the testing proposed herein. At the time of publication, the edition indicated was valid. All standards are subject to revision, and the most recent edition of the standard listed below should be consulted.

ASTM E837 20, "Determining residual stresses by the hole drilling strain-gauge method."

This standard together with the Welwyn Strain Measurement Technical Note TN-503-3 forms the basis of this guide which is focused specifically on polymeric materials

3.3 Equipment

- 3.3.1 Hand-driven mill for drilling a hole with a flat bottom and diameter of about 1.5 mm to a controlled depth.
- 3.3.2 A three element strain gauge rosette exemplified by Figure 7

3.4 Test specimen

- 3.4.1 The geometry of the test specimen is not critical provided that it is sufficiently flat in the region of measurement.

3.5 Procedure

- 3.5.1 Clean the surface with a suitable cleaning fluid to remove any dirt that may prevent the gauges from adhering to the surface of the polymer.

Note. Care should be taken when selecting a suitable cleaning fluid as certain fluids may attack the polymer or induce plasticisation that will effect the residual stresses.

- 3.5.2 Bond the strain gauges to the surface of the polymer using an adhesive.

Note. The adhesive should not affect the properties of the polymer and the choice of adhesive should be modified accordingly. A cyanoacrylate adhesive is suitable for many systems.

- 3.5.3 In attaching the strain gauge rosette to the sample, the orientation of strain gauge 1 (Fig 7) relative to the orientation of the plate (eg melt flow direction) or component should be noted.

- 3.5.4 Attach wires to each of the strain gauges on the rosette using a soldering iron.

Note 1. As the heat of the soldering iron can affect the residual stresses in the polymer care should be taken whilst soldering not to expose the specimen to high temperatures over long periods of time.

Note 2. It is advisable to attach a small pad next to the rosette to which the wires from the strain meter and the rosette can be attached. This will reduce any strain in the rosette induced by the movement of the wires.

- 3.5.5 Attach the mill firmly to the specimen and ensure that the mill is completely horizontal using a spirit level.

Note. The mill should be chosen to give the desired diameter of hole (see 3.5.11).

- 3.5.6 Using an optical microscope attachment align the mill so that the cross-wires are precisely in the centre of the strain gauge rosette

- 3.5.7 Replace the microscope attachment with the mill cutter (Figure 8) and carefully drill through the centre of the rosette and the underlying adhesive minimising penetration of the substrate.

- 3.5.8 Record the strain on each gauge with the mill just resting on the surface.

Note. There may be some transient variation in the strain values. Whenever measuring strain, a short period should be allowed (several minutes) to allow the values to attain steady state before recording the value.

- 3.5.9 Drill the hole to the required depth (using the micrometer on the mill) and then turn back the cutter to free any swarf that may be trapped in the hole.

Note 1. As excess heat may affect the residual stresses in the plastic all the milling should be done by hand. When a reading is made the mill is left in the hole as removing the mill may affect the strain gauge measurements.

Note 2. Care should be taken to ensure that the milling proceeds in the vertical plane with minimal side pressure or friction. The process generates a hole which is approximately flat-bottomed.

Note 3. Holes are drilled usually in depth increments of about 0.1 mm.

- 3.5.10 Record the depth of hole.

- 3.5.11 After drilling to the required depth, the drill is left in the hole and the strain measurements recorded.

Note. The surface strains associated with the stress relaxation due to hole drilling diminish with hole depth and become insignificant for depth to diameter ratios greater than 0.5.

- 3.5.12 To determine the values of the parameters A and B (see 3.6) prepare an annealed flat strip of the material and conduct the hole-drilling procedure that is outlined whilst the strip is subjected to a known stress in tension.

3.6 Analysis of results

The derivation of the in-plane stresses is calculated from (Welywn Measurement Note 503-3):

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

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

$\sigma_{\max}$ and $\sigma_{\min}$ are the maximum (most tensile) and minimum (most compressive) principal stresses present at the hole location before drilling. ε_1 , ε_2 , ε_3 are the relieved strains as measured by the correspondingly numbered, radially orientated strain gauges (Fig 7).

The parameters A and B should be determined experimentally, see 3.5.12.

To establish the direction of the stresses, calculate α with respect to strain gauge 1 (see Fig 7) using

$$\tan \alpha = \frac{\varepsilon_1 - 2\varepsilon_2 - \varepsilon_3}{\varepsilon_3 - \varepsilon_1} \quad (5)$$

The following rules apply:

$\varepsilon_3 > \varepsilon_1$:	α refers to $\sigma_{\max}$
$\varepsilon_3 < \varepsilon_1$:	α refers to $\sigma_{\min}$
$\varepsilon_3 = \varepsilon_1$:	σ refers to $\pm 45^\circ$
$\varepsilon_2 < \varepsilon_1$ at $+45^\circ$	
$\varepsilon_2 > \varepsilon_1$ at -45°	

An example of the variation of residual stress through the thickness of an injection-moulded polymer specimen is shown in Figure 9.

3.7 Test report

The test report shall include the following information:

- (a) full description of the material from which the specimens were taken including the processing history;
- (b) description of the form of the material and the location from which specimens were removed;
- (c) elapsed time and storage conditions after processing;
- (d) description of the hole drilling procedure including bonding agent, hole diameter and maximum depth;
- (e) example of strains measured;
- (g) analytical procedure for determining residual stress;
- (h) residual stress variation through the thickness of the specimen in two dimensions, with statement of uncertainty.

Chapter 4: Chemical probe method

- Principle
- Normative references
- Equipment
- Test specimens
- Environments
- Test temperature
- Procedure
- Test report

4. Chemical probe method

4.1 Principle

The chemical probe technique is based on establishing reference environment stress cracking (ESC) data for the relationship between stress and time to crazing and/or cracking for specific polymer-environment combinations with the polymers in the annealed state. 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. The method is useful primarily for indicating near-surface tensile stresses. The technique is not constrained to specific geometries, although multi-axial residual stresses in complex components may create some uncertainty in the values.

4.2 Normative references

The following standards provide useful background for conducting the testing proposed herein. At the time of publication, the editions indicated were valid. All standards are subject to revision, and the most recent editions of the standards listed below should be consulted.

- BS EN ISO 22088-2:2006 Plastics. Determination of resistance to environmental stress cracking (ESC). Constant tensile load method
- BS EN ISO 22088-3:2006 Plastics. Determination of resistance to environmental stress cracking (ESC). Bent strip method

4.3 Equipment

4.3.1 Facility for subjecting specimen to constant applied load or constant displacement.

Note 1. In constant displacement testing, four-point bend is preferred relative to the three-point bend because of the extended region of uniform tensile stress between the loading points.

Note 2. A four-point bend jig capable of testing a number of specimens simultaneously is advantageous.

4.3.2 Inert cell for containing test fluid

Note. A transparent cell shall be used for constant load testing.

4.4 Test specimens

- 4.4.1 The test specimens used to determine the threshold stress under constant load conditions shall conform to ISO 20753:2023.

Note. The standard small tensile specimen with an overall length of 75 mm and a gauge length of 30 mm is suitable for many applications. The width of the gauge section is 5 mm and that of the end section is 10 mm.

- 4.4.2 The specimens for four point bend tests shall be prepared in conformity with ISO 22088-3:2006.
- 4.4.3 The edges of the specimens shall be polished to a 1200 grit finish to minimise the impact of machining defects on the crazing and cracking process.
- 4.4.4 The specimens used to establish the reference stress - time-to-craze(crack) data shall be annealed to relieve pre-existing residual stresses.

Note. Annealing for two days at 6 °C below the glass transition temperature followed by slow cooling is sufficient for most materials.

4.5 Environments

- 4.5.1 The choice of test environment depends on the material.
- 4.5.2 Analytical reagent grade chemicals shall be used for all chemicals where possible unless simulating service environments.

4.6 Test temperature

The temperature of the testing shall normally be $23 \pm 2^\circ\text{C}$.

4.7 Procedure

4.7.1 *Determination of threshold stress using constant load testing.*

- 4.7.1.1 The sample shall be mounted in the test cell and then in the grips.

Note 1. For environmental chambers for which the grips are immersed, a grip with a rippled contact surface is useful in avoiding failure at the grips.

Note 2. The edges of samples may act as the sites for craze initiation. Since such edges do not exist in the same form when testing the material, there

is a possibility of some impact on the estimated residual stress. This possibility can be tested by clamping small environmental cells, e.g. modified UV cells, directly onto the faces of the specimen.

4.7.1.2 The load shall be applied.

4.7.1.3 The environment shall be added to the cell with minimal delay.

4.7.1.4 The load shall be maintained until crazing extends across the width of the specimen (or fracture of the specimen), or until the elapsed time exceeds an appropriate test period.

Note 1. The surface of the sample shall be examined in-situ at appropriate intervals, with the period depending on the severity of the environment, to assess the extent of crazing.

Note 2. The test period should be sufficient to interpret sensibly the results of exposure of processed samples to the environments. Because of possible relaxation in the latter case, the value of very long term tests is limited. Test periods of the order of minutes/hours rather than days would be appropriate.

4.7.1.5 Steps 4.7.1.1 to 4.7.1.4 are repeated for a series of applied loads with at least two specimens examined for each load.

Note. The range of loads applied should be optimised for the degree of accuracy required for the measurement process.

4.7.1.6 The applied stress against time-to craze/fracture shall be plotted as illustrated in Fig 10.

4.7.1.8 Steps 4.7.1.1 to 4.7.1.6 shall be repeated for a series of environments of varying severity.

Note. The range of environments depends on the desired accuracy required in estimation of residual stress in the processed samples.

4.7.2 *Determination of threshold stress using four-point bend testing.*

4.7.2.1 The specimen shall be mounted in the four point bend jig and a measured displacement applied to achieve the desired initial stress (tensile stress at the outer fibres) on the specimen.

4.7.2.2 The jig shall be immersed immediately in the test fluid.

4.7.2.3 After the desired exposure interval, the specimen shall be inspected for crazing.

Note. In constant displacement testing, relaxation of stresses with time often means that cracking does not ensue unless the stress is high enough to initiate cracking in a short period of time. 'Failure' is defined as the observation of a craze extending across the whole width of the specimen, if no fracture occurs.

- 4.7.2.4 Steps 4.7.2.1 to 4.7.2.3 shall be repeated at different initial stresses with at least 5 test specimens at each stress.

Note. The use of a jig capable of testing up to 5 specimens simultaneously is a considerable advantage in the latter case. A profiled jig generating varied stress along the specimen length may also be used. However, in the latter case relaxation due to the onset of crazing in one region may affect the behaviour in adjacent regions.

- 4.7.2.5 The initial tensile stress on the outer fibres against time-to fracture shall be plotted as illustrated in Figure 11.

- 4.7.2.6 Steps 4.7.2.1 to 4.7.2.5 shall be repeated for a series of environments of varying severity.

Note. The range of environments depends on the desired accuracy required in estimation of residual stress in the processed samples.

4.7.3 *Determination of residual stress.*

- 4.7.3.1 The test cell shall be clamped to the test material and the environment added.

- 4.7.3.2 The material shall be inspected for crazing and cracking at regular intervals.

Note. The inspection interval can be defined in relation to Figures 10 and 11.

- 4.7.3.3 This process shall be repeated for the range of environments utilised in 4.7.1 and 4.7.2.

- 4.7.3.4 The magnitude of residual stress shall be evaluated based on the observation or otherwise of crazing/cracking as a function of environment severity and using reference plot as exemplified by Figures 10 and 11.

4.8 Test report

The test report shall include the following information:

- (a) full description of the material from which the specimens were taken including the processing history;
- (b) elapsed time and storage conditions after processing;
- (c) description of the form of the material and the location from which specimens were removed;
- (d) specimen type and dimensions;
- (e) the environments tested;
- (f) description of the test method used for establishing reference stress - time-to-craze/crack data;
- (g) a description of the apparatus and exposure conditions;
- (h) the temperature of testing;
- (i) plots/tables of applied stress versus time to fracture;
- (j) estimated residual stress and uncertainty.

Chapter 5: References and figures

5. References

1. Treuting R.G and Read W.T., J.Appl.Phys.,22, 130, (1951)
2. White J.R., Polymer Testing, 4, 165-191, (1984)
3. Turnbull A., Maxwell A.S. and Pillai S., Residual Stress in Polymers - Evaluation of Measurement Techniques, Journal of Material Science, 34, 451-459, (1999)

6. Figures

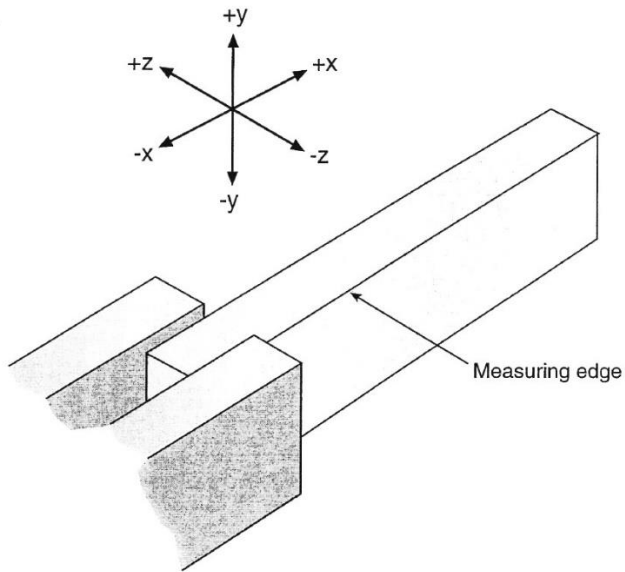


Figure 1: Specimen confirmation for optical measurement of curvature.

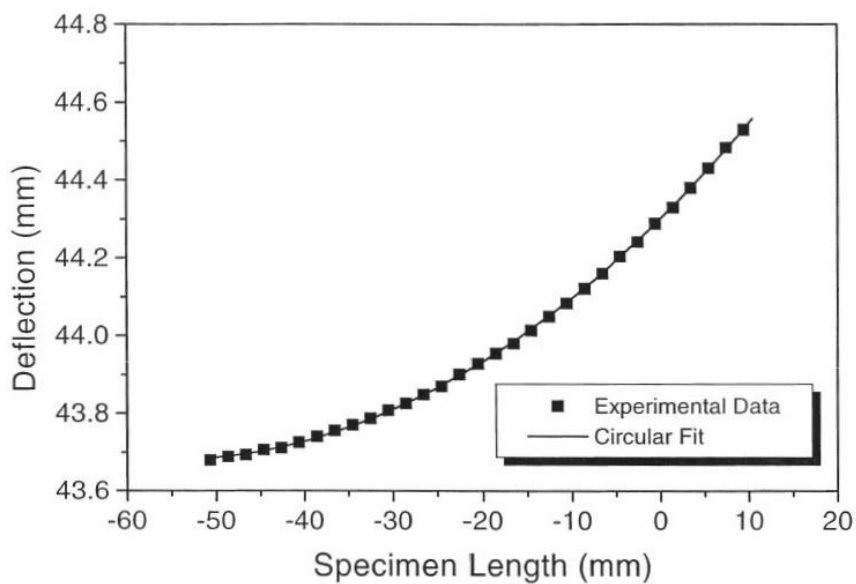


Figure 2: Circular fit used to determine the curvature of an unfilled ABS specimen.

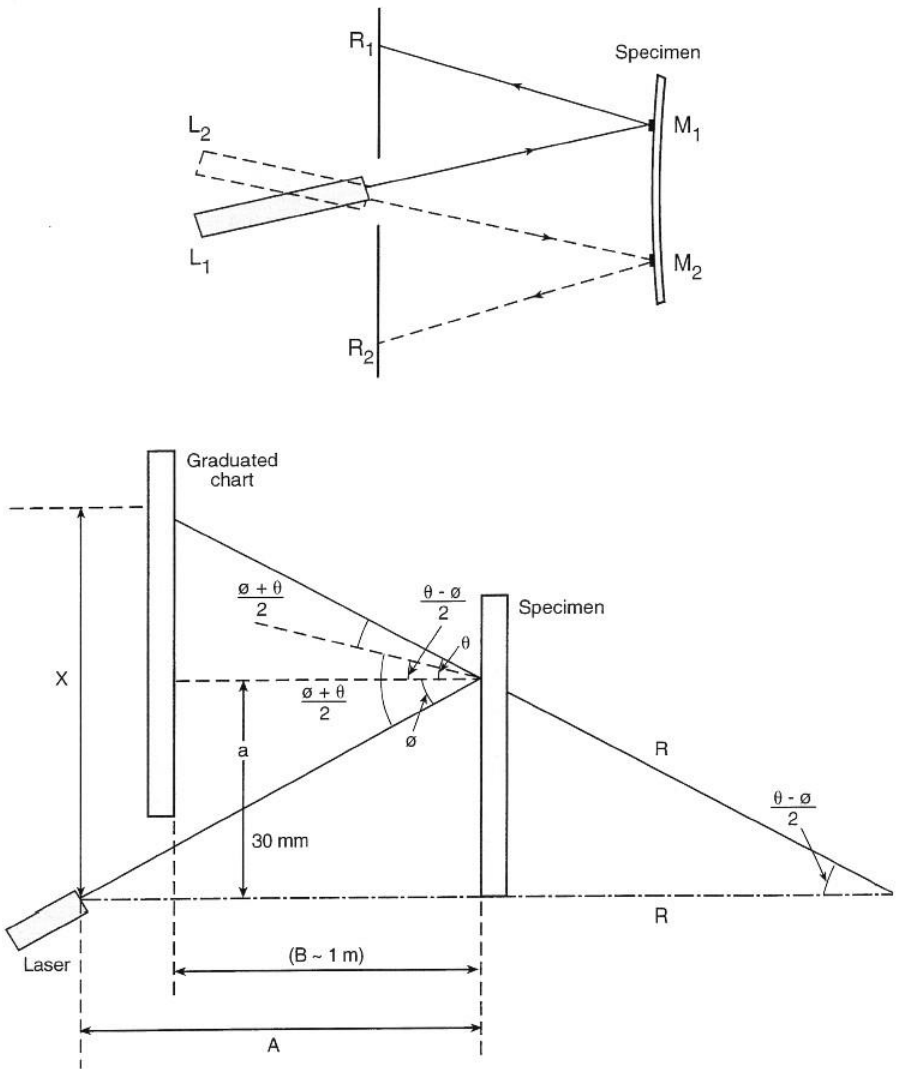


Figure 3: Arrangement for measuring the curvature of a bar clamped at its centre. The position on the screen, S, of the reflection, R₁, from mirror, M₁, with the laser in position L₁, is recorded, then the laser is rotated to position L₂ to produce reflection R₂ from M₂.

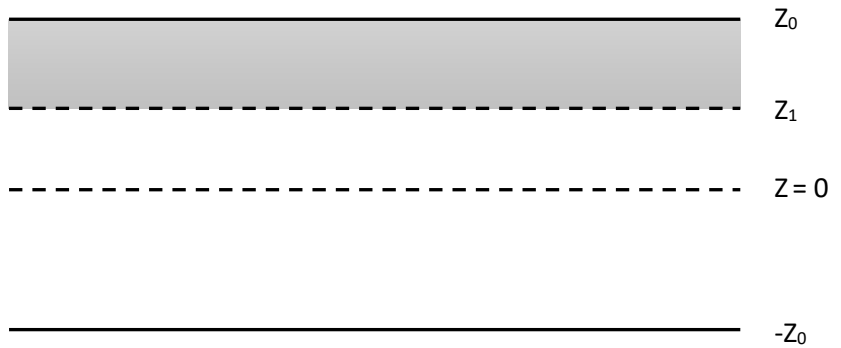


Figure 4: Cross section of a flat parallel-sided moulding showing the mid-plane prior to machining at $z=0$, the as-moulded surfaces at $z=\pm z_0$ and the surface after machining away layers from the upper half of the bar at $z=z_1$.

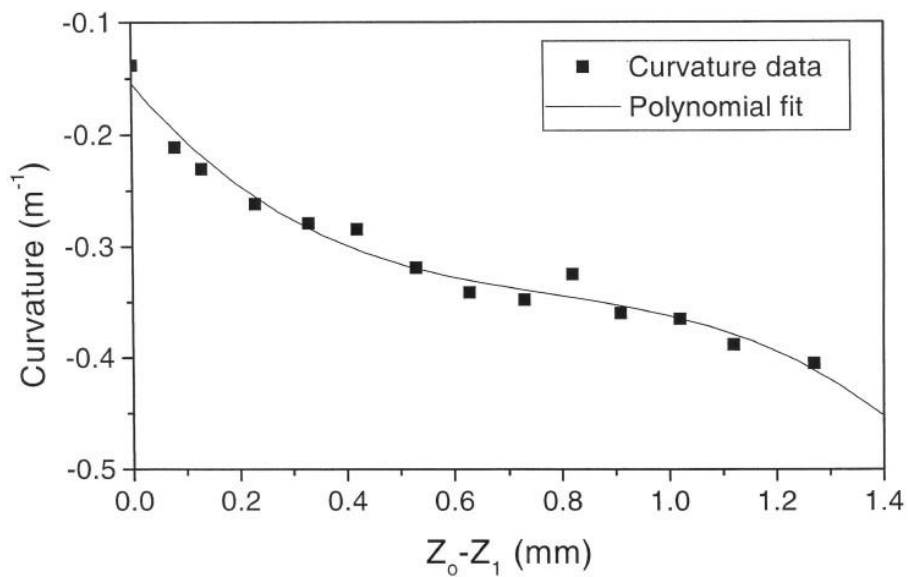


Figure 5: Third order polynomial fit to data for a specimen of unfilled ABS.

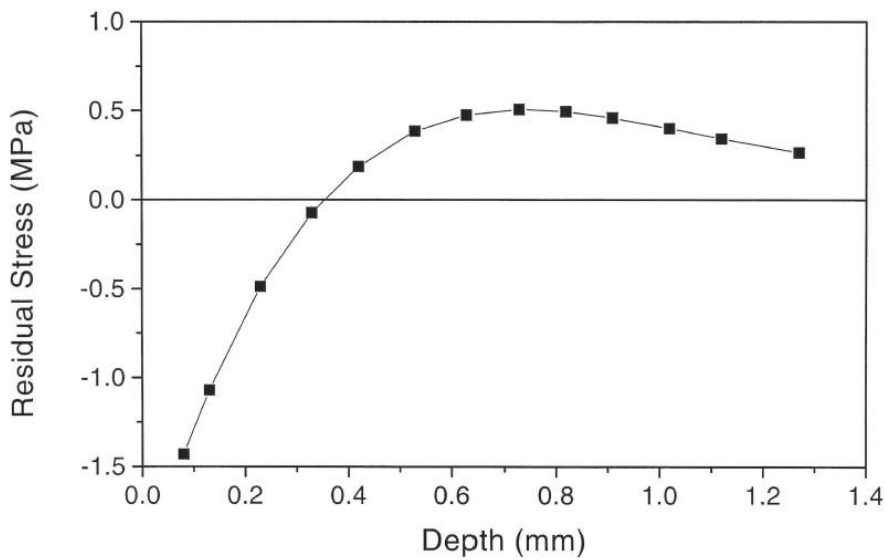


Figure 6: Residual stress in specimen of unfilled ABS examined using the layer removal technique.

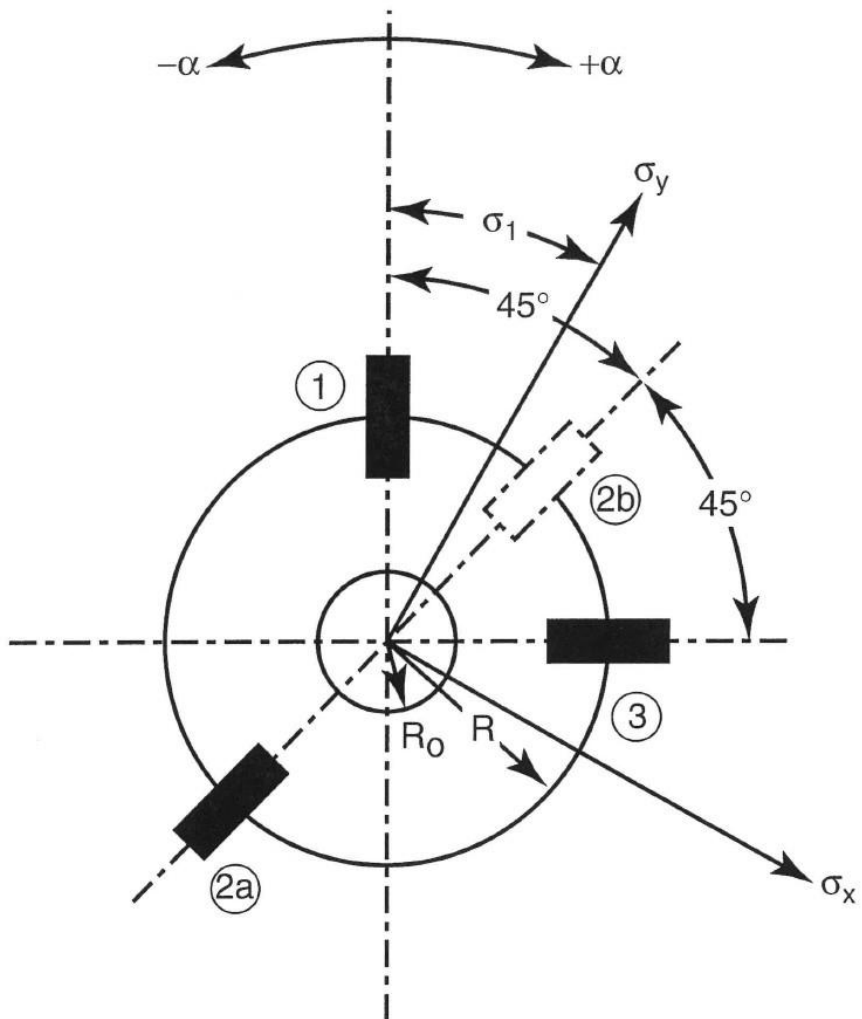


Figure 7: Positioning of the strain gauges on the specimen surface in the hole drilling technique

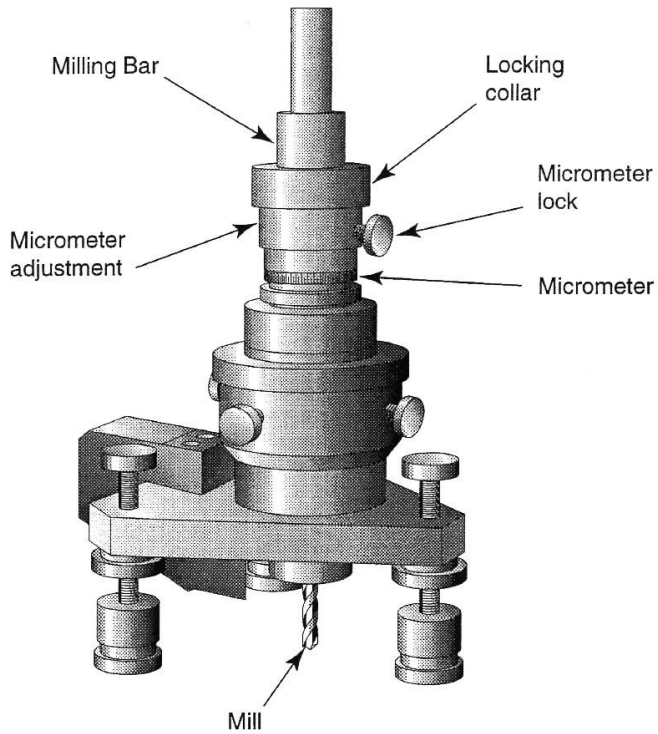


Figure 8: Schematic diagram of the hole drilling apparatus

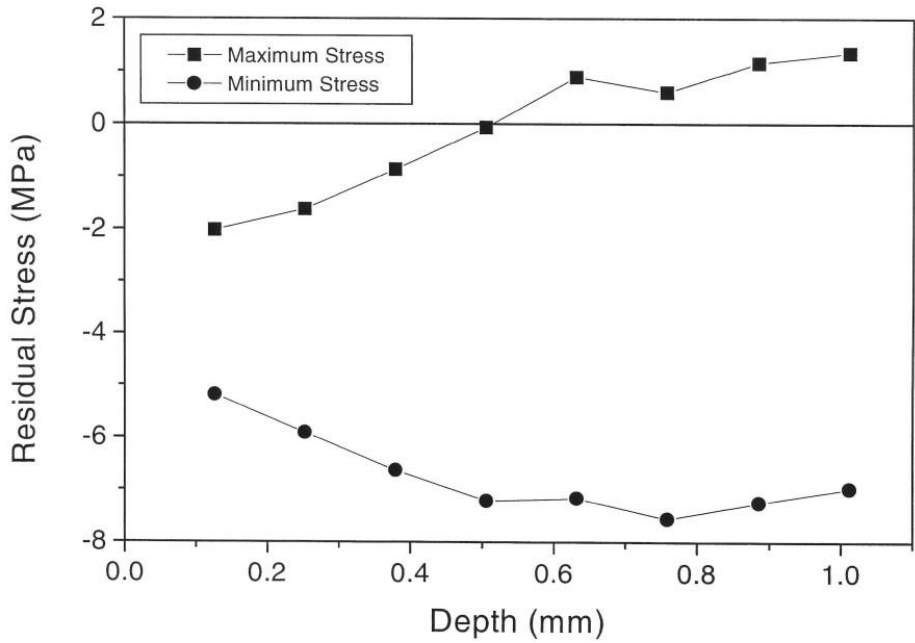


Figure 9: Hole drilling results obtained along the two principle axes in unfilled ABS.

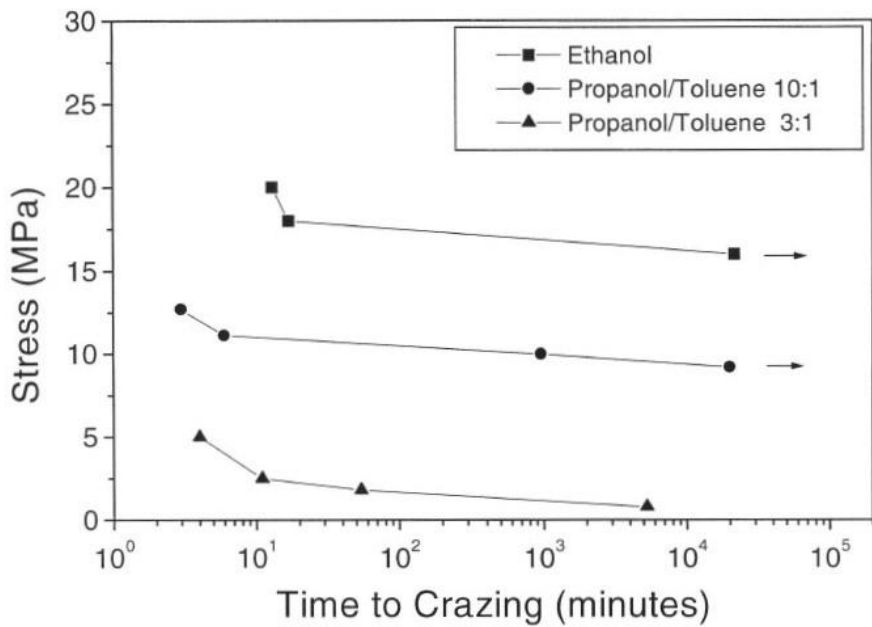


Figure 10: Effect of environment on the ESC of Polycarbonate under constant load.

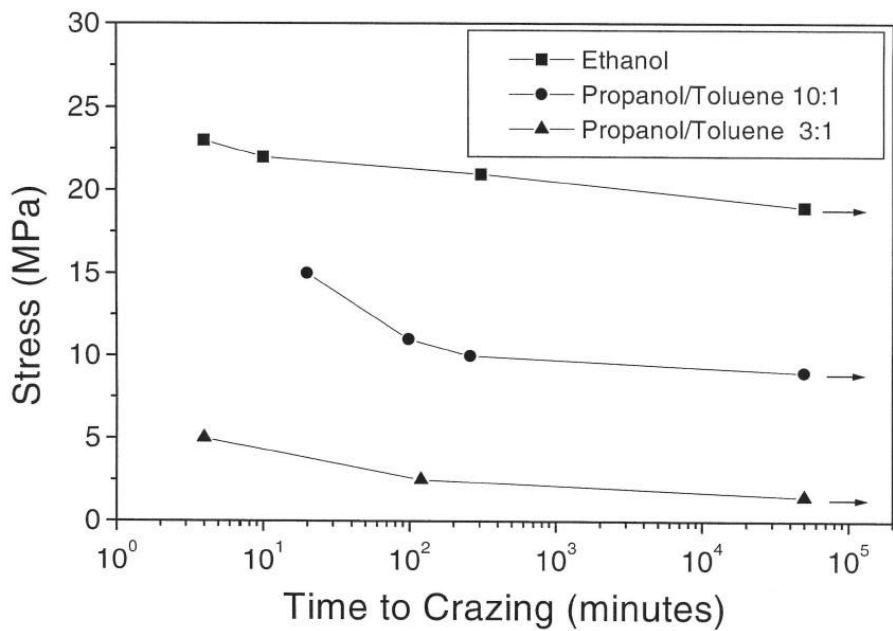


Figure 11: Effect of environment on ESC of Polycarbonate under 4 point bend.