Measurement of Residual Stress in Plastics

An evaluation has been made of the effectiveness of the chemical probe and hole drilling techniques to measure the residual stresses present in thermoplastic injection-mouldings. Modifications to the chemical probe technique are outlined that enable the technique to be used to measure the compressive residual stresses that are found at the surface of many injection-moulded plastic components. Alterations to the hole drilling technique are also described that reduce the heat generated during the drilling process enabling more accurate results to be obtained. Residual stress data obtained from both the chemical probe and hole drilling techniques have been compared to values obtained using Sigmasoft injection-moulding simulation software.

A S Maxwell

August 2005

1   Introduction

Thermoplastic injection-mouldings contain residual stresses that are the consequence of differential cooling rates through the thickness of the mould. Although these stresses are commonly found in plastics their magnitude can be extremely difficult to predict as they depend upon a wide range of variables including the mould design, material and processing parameters. These stresses can significantly reduce the life expectancy of polymer products, increasing the likelihood of dimensional instability (warpage) and environment stress cracking.

Current methods for detecting residual stress in plastics include birefringence [1], layer removal [2], hole drilling [3-7] and the chemical probe technique [8]. All of these techniques have their limitations.

The birefringence technique measures changes in the optical properties of a polymer that occur when residual stresses are present. Birefringence has obvious limitations for non-transparent materials and analysis of residual stress can be complicated by molecular orientation induced during processing.

The layer-removal technique involves measuring the degree of curvature introduced into flat plate samples by the removal of thin layers from the surface of the specimen. By measuring the curvature in the specimen it is possible to determine the strain and hence the residual stresses that are present in the layer that is removed. Although it is an accurate technique it is extremely time consuming and in most cases is impractical as it can only be used on flat plates.

Hole drilling involves locally relieving residual stress by drilling a small hole into the surface of the polymer. Measuring the strain around the hole it is possible to determine the residual stresses that are present in the polymer. Hole drilling is widely used for measuring residual stress in metals. However, its use with plastics is limited due to large errors that can result from localised heating that often occurs during the drilling process [5]. Nevertheless hole-drilling is a promising technique and will be considered further in this study.

The chemical probe technique is a quick and simple technique, suitable for use in quality control applications. The technique involves applying chemicals to the surface of a polymer and measuring the time taken for the polymer to fracture. The higher the residual stresses in the polymer the quicker it will fracture due to environmental stress cracking (ESC). The main problem with this method is that it can only detect tensile residual stresses whereas most stresses in injection-mouldings are compressive.

This report describes a study that has been conducted using new hole drilling apparatus that minimises the heat that builds up during the drilling process by using a drill bit that spins in an orbital motion during the drilling process. The study has also involved the development of a new chemical probe technique that can be used to examine the compressive residual stresses found in injection mouldings and which can be conducted on the shop floor by relatively unskilled operators. To validate these techniques the results from the hole drilling and chemical probe techniques have been compared to predictions of residual stress made using commercially available simulation software (Sigmasoft).

2   Chemical Probe

2.1 Introduction

The chemical probe technique is based on establishing reference ESC data for the relationship between stress and time to fracture of a polymer in a specific chemical environment. When a plastic with unknown residual stress is exposed to the same environment, the time required for cracks or crazes to develop can be used to predict the magnitude of the unknown residual stresses in the plastic.

In this study the chemical probe was used to examine the residual stress in injection-moulded preforms that are used in the production of plastic drink bottles. Residual stress is a particular problem in preforms as it can cause bottles to fail when they are blow-moulded. One technical problem that had to be overcome is that the residual stresses on the surface of the preforms are compressive rather than tensile, which cannot be detected using conventional chemical probe techniques. This has been overcome by applying an external pressure to make the resultant stress tensile.

2.2 Instrumentation

A prototype instrument was designed that applied additional tensile stress to the preforms by pressuring them internally using nitrogen gas (Figure 1). Bottle preforms, filled with ethanol, were screwed into a holder, attached to a gas supply (nitrogen) that was fitted with an in-line pressure gauge. A known pressure was then applied to the preforms, which were housed in a metal cover for safety. The ethanol in the preforms acted as a stress-cracking agent in the presence of surface tensile stresses, which were generated by the pressure of the gas. The preforms increased in volume due to crazing and plasticisation causing the pressure to fall over time. Thus the performance of different preforms could be easily compared measuring the time required for the pressure in the preforms to drop. This can be used to determine the amount of residual stress in the preforms through comparisons with a calibration curve produced using annealed preforms in which the residual stress has been removed.

Figure 1   Chemical probe instrumentation designed for use with bottle preforms.

2.3 Measurements

A calibration curve was produced by annealing a series of preforms to remove the residual stresses. These preforms were filled with ethanol and tested using the chemical probe over a range of pressures between 20 and 50 bars. The time required for the preforms to fracture was then recorded and plotted against the applied gas pressure to produce a calibration curve (Figure 2). A preform containing unknown levels of residual stress was then taken and tested using the same chemical environment. Applying an internal pressure of 40 bar to the preform caused crazing to occur after 60 minutes compared to 15 minutes for an annealed preform at the same pressure. The increased time required for the preforms to craze is due to compressive residual stresses in the moulding. Using the calibration curve it is possible to determine that the additional pressure required to craze the preform was 20 bar. It can therefore be concluded that the residual stress in the preform is equivalent to an applied gas pressure of 20 bar. An FEA mesh was then used to calculate the stresses that a 20 bar pressure would produce in the moulding, from which it was calculated that the mouldings must have contained compressive residual stresses of 15 ± 5 MPa.

2.4 Comparison with simulation

Working in collaboration with RAPRA, the results from the chemical probe technique have been compared to residual stress values obtained from Sigmasoft. This is a commercial software package that simulates the injection moulding process using a 3D model. By simulating both the heating and cooling stages of the injection moulding process Sigmasoft predicts the residual stresses that develop in the mould. Using the same mesh as was used in the FEA analysis it was found that Sigmasoft predicted residual stresses in the preforms of between 7 and 25 MPa (Figure 3). These results are sufficiently close to those obtained using the chemical probe technique (15 ± 5 MPa) to be used for most design purposes.
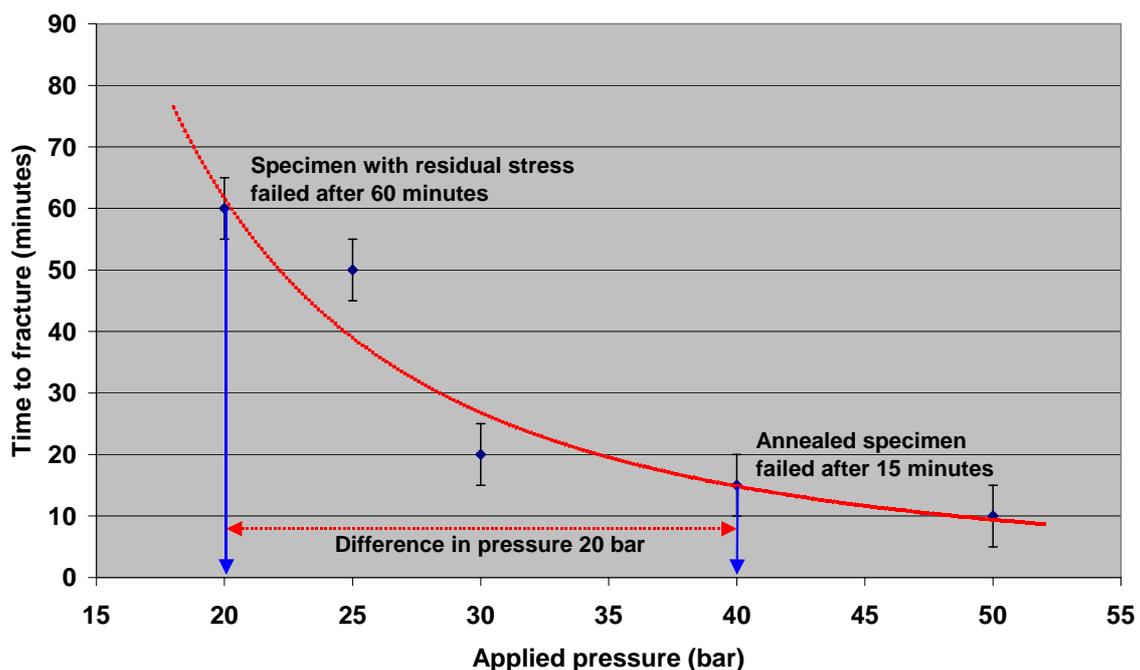

Figure 2   **Chemical probe calibration curve for residual stress in preforms.**
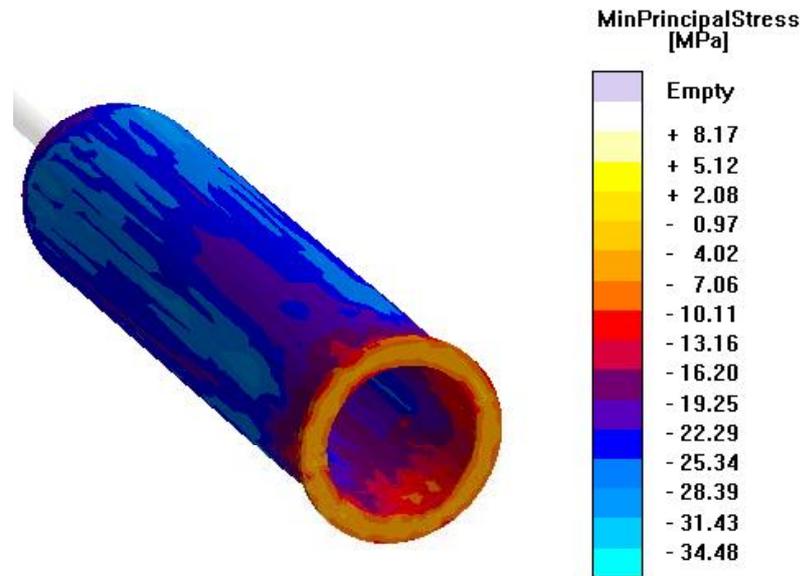
Figure 3 Sigmasoft simulation predicts residual stresses in the preform of between 7 and 25 MPa

3 Hole-drilling

3.1 Introduction

Hole drilling is potentially a more flexible technique than the chemical probe due to the fact that it is able to determine values of residual stress at different positions within mouldings and at different depths. The hole drilling technique involves fixing a rosette of strain gauges to the surface of the specimen and then drilling a hole precisely through the centre of the rosette. The strains produced at the surface reflect the residual stresses that have been removed during the drilling process. Using appropriate models, the measured strains can be used to calculate the stresses for the principal axes in the plane of the sample.

Whilst hole drilling is widely used for the measurement of residual stress in metals [3] its use with plastics has been limited due to the sensitivity of plastics to the changes in temperature and pressure that occur during the drilling process. The work described in this measurement note investigates whether reliable residual stress measurements can be obtained from plastics using the hole drilling technique. To limit errors induced by the frictional heating of the drill in the hole, a drill bit that spins in an orbital motion around the hole was used. This allowed air to circulate around the hole to cool the drill and prevent swarf becoming trapped in between the drill bit and the edges of the hole.
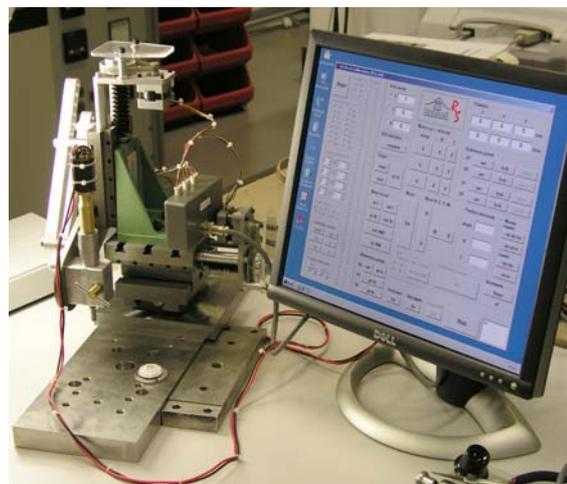

Figure 4   **Hole drilling NPL Stresscraft 3D Equipment**

3.2 Procedure

Following degreasing and light surface preparation the strain gauge rosettes were bonded to the specimen using cyanoacrylate adhesive. The drill was positioned at the centre of the rosette using an optical microscope. Holes were drilled in 8 depth increments (h) of 0.128 mm with a drill diameter of 1.6 mm and an offset of 0.3 mm. At each depth, the readings on the strain gauges were allowed to stabilise for about 3 minutes before measurements were taken. The residual stresses in the specimen were then calculated at each hole depth using the readings obtained from the strain gauge measurements.
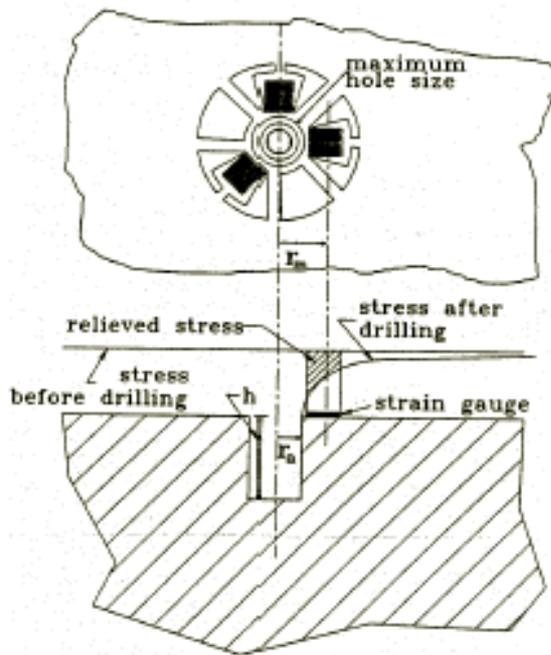

Figure 5 Arrangement of strain gauges on the surface in the hole drilling technique.

The conventional analysis procedures described in ASTM E837 [3] and the Measurements Group TN TN-503-3 [4] are only applicable for situations where the residual stress is uniform and does not vary significantly with depth. This is not the case for the materials examined in this study, and results were therefore analysed using the *Integral method* approach, which has been developed by Schajer [6] and allows analysis of hole drilling data in non-uniform residual stress fields. The integral approach requires different sets of coefficients to relate the surface strain changes to the residual stress present for each of the stress depth and hole depth combinations. Further examples and details are given in NPL Good Practice Guide No 53 [7].

3.3 Measurements

Values for the maximum residual stresses in three different polymeric mouldings have been determined using this hole drilling technique (Table 1). In each of the mouldings the maximum tensile stress was found beneath the surface of the moulding (Figure 5). This is typical of the residual stresses that are found in injection-mouldings with large compressive stresses close to the surface and tensile stresses beneath.

Table 1   Values for the maximum residual stress of 3 industrial mouldings obtained using hole drilling and Sigmasoft.

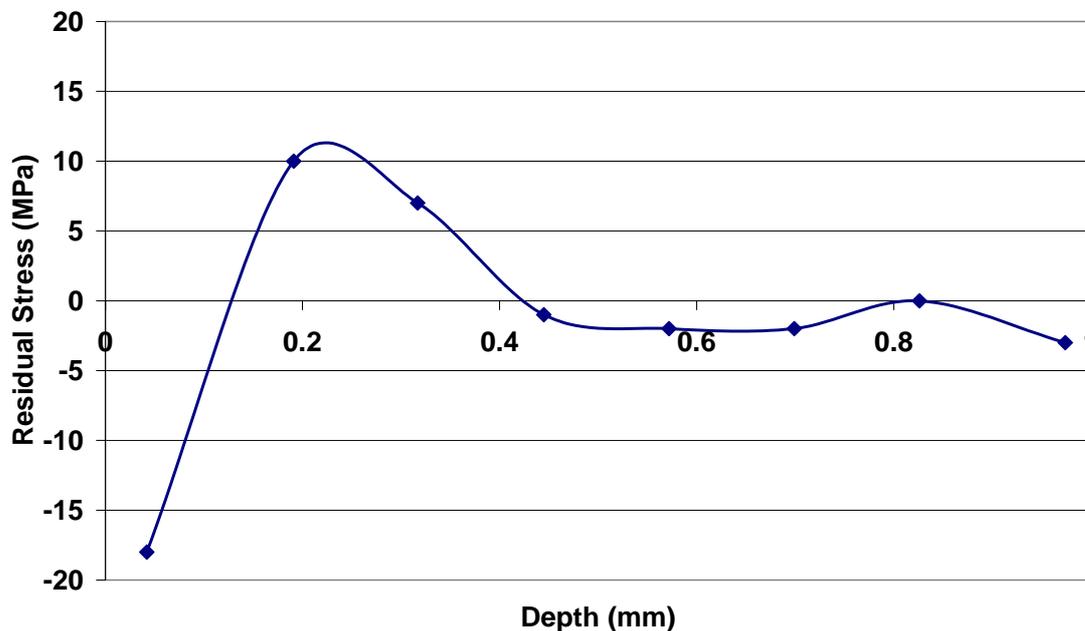| Moulding	Material	Hole drilling (MPa)	Sigmasoft (MPa)
Switchgear	Polyurethane thermoset	10 ± 4	11
Peristaltic pump	Polyphenylene sulphide 40% glass fibre filled	5 ± 4	3
Engine management unit	Polycarbonate / Polybutylene terephthalate	11 ± 4	10

Figure 5   **Residual stress along the principle axis of the engine management unit measured using hole drilling.**

This type of distribution occurs because rapid cooling of the mould causes the surface of the polymer to solidify before the core. Once the outer surface has solidified subsequent cooling causes the core to shrink due to thermal contraction. This shrinkage is, however, constrained by the skin of the moulding that is already solid. As a consequence, tensile residual stresses form in the core, which are balanced by compressive stresses in the skin, as can be observed in the hole drilling results (Figure 5).

Again working in collaboration with RAPRA, the results from the hole drilling technique have been compared to the values that have been predicted using the Sigmasoft package (Table 1). As can be seen the maximum tensile residual stresses that have been obtained by Sigmasoft are all consistent with the results that have been obtained with the hole drilling technique. Furthermore, as with the hole drilling results the

maximum tensile residual stresses were all found to occur just beneath the surface of the moulding.

4 Conclusions

The use of compressed gas to exert a tensile stress on injection-mouldings has enabled the chemical probe technique to be used to measure compressive residual stresses in injection-mouldings. Modifications to the hole drilling technique using a drill bit that will reduce the heat and pressure generated during the drilling process demonstrates that the hole drilling technique can be successfully used with plastics. Finally residual stress measurements made using the chemical probe and hole drilling techniques have been shown to be consistent with the values obtained from the Sigmasoft injection-moulding simulation software.

References

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7) NPL Good Practice Guide No. 53. "The Measurement of Residual Stresses by the Incremental Hole Drilling Technique – Issue 2" P.V. Grant, J.D. Lord and P.S. Whitehead, Sept 2005
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Acknowledgements

For further information contact:

Dr Tony Maxwell
Process Materials
National Physical Laboratory
Hampton Road
Teddington, Middlesex.
TW11 0LW

Telephone: 020 8977 3222 (*switchboard*)
Direct Line: 020 8943 6454
Fax: 020 8943 6177