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On the Determination of Stress-Strain Curves under Biaxial Loading Conditions

P E Tomlins*, M Yazici⁺ and G D Dean*

***Centre for Materials Measurement and Technology
National Physical laboratory
Teddington, Middlesex
United Kingdom, TW11 0LW**

**⁺University of Essen
Essen, Germany**

SUMMARY

In practice obtaining biaxial stress-strain curves for plastics is difficult due to the problems of designing suitable testpieces, test rigs and calculating the stress in the region where the sample deformation is measured. A number of different test geometries have been published that include tubes, films and a variety of cruciform structures. These structures have generally been used to measure small strain deformation or the growth of cracks. In this report we describe the practical problems associated with measuring large strains i.e. the onset of plastic deformation in cruciform specimens manufactured from ABS and propylene-ethylene copolymer.

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National Physical Laboratory
Teddington, Middlesex, UK, TW11 0LW

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Head of Centre for Materials Measurement & Technology

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1 INTRODUCTION

Modelling the deformation behaviour of components of complex geometry, e.g. the housing for a mobile phone, relies on constitutive models that are able to predict the strain induced by multiaxial stresses. The modelling process for linear deformation behaviour relies on resolving the stress into its tensor components. The strain attributable to each of these components is then calculated and summed to give the strain state. However, if the stress levels exceed the limit for linear stress-strain behaviour then these equations are insufficient. The onset of non-linearity in glassy plastics is explained in terms of viscoelastic deformation mechanisms in the material that become non-linear at high stresses and moderate strains. At even higher strains, these mechanisms give rise to extensive plastic flow in tough plastics. Constitutive laws for describing non-linear viscoelasticity are few and complicated. In finite element packages, non-linear behaviour is described using elastic-plastic relationships developed for metals and certain other materials. These are not generally applicable to plastics without incurring uncertain and, in some situations, large errors. A new model is being developed as part of this project (Read et al¹). The parameters in this model can be derived from tests under shear, uniaxial tension and uniaxial compression. In order to provide an evaluation of the wider validity of the model, further data are required under a different stress state for comparison with predictions using the model. In this report we describe different methods for measuring non-linear biaxial stress-strain curves for two materials.

There are a number of designs for biaxial testing rigs within the literature (Radon et al², Wanders³, Sweeney⁴). These rigs have been designed for specific applications e.g. film stretching at elevated temperatures, monitoring fatigue crack growth or measuring the strain in response to applied unbalanced biaxial stresses.

1.1 TEST SPECIMEN GEOMETRY

The test specimen geometry and the design of the clamping arrangement are critical to obtaining good data. Previous investigators have applied biaxial stresses to tubes (Zeibs et al⁵), films (Sweeney et al^{4,6}) and cruciform plate specimens (Monch and Galster⁷, Leever et al⁸). These different designs each have their own idiosyncrasies that are discussed below and the choice of specimen geometry depends on the nature of the measurement e.g. slow crack growth or continuous material deformation.

1.1.1 Films

Biaxially stretching films above their glass transition temperature, T_g is used to manufacture sheet material that is used in packaging as well as for manufacturing audio and video tape. The latter applications require high levels of dimensional stability coupled with specific surface finishes. Typically very high stretching rates e.g. $>3600\% \text{ min}^{-1}$ are used during testing (Cakmark and Simhambhatla⁹).

1.1.2 Tubes

Investigations of, for example, the fatigue performance of composite materials under biaxial loading often utilise tubular structures that are relatively easy to manufacture using filament winding techniques (Fujii and Lin¹⁰, Owen et al¹¹). The tubular design often has a waisted central section where the displacement is monitored. The biaxial stress is applied to the test piece by simultaneously twisting and stretching the tube. In this type of specimen geometry

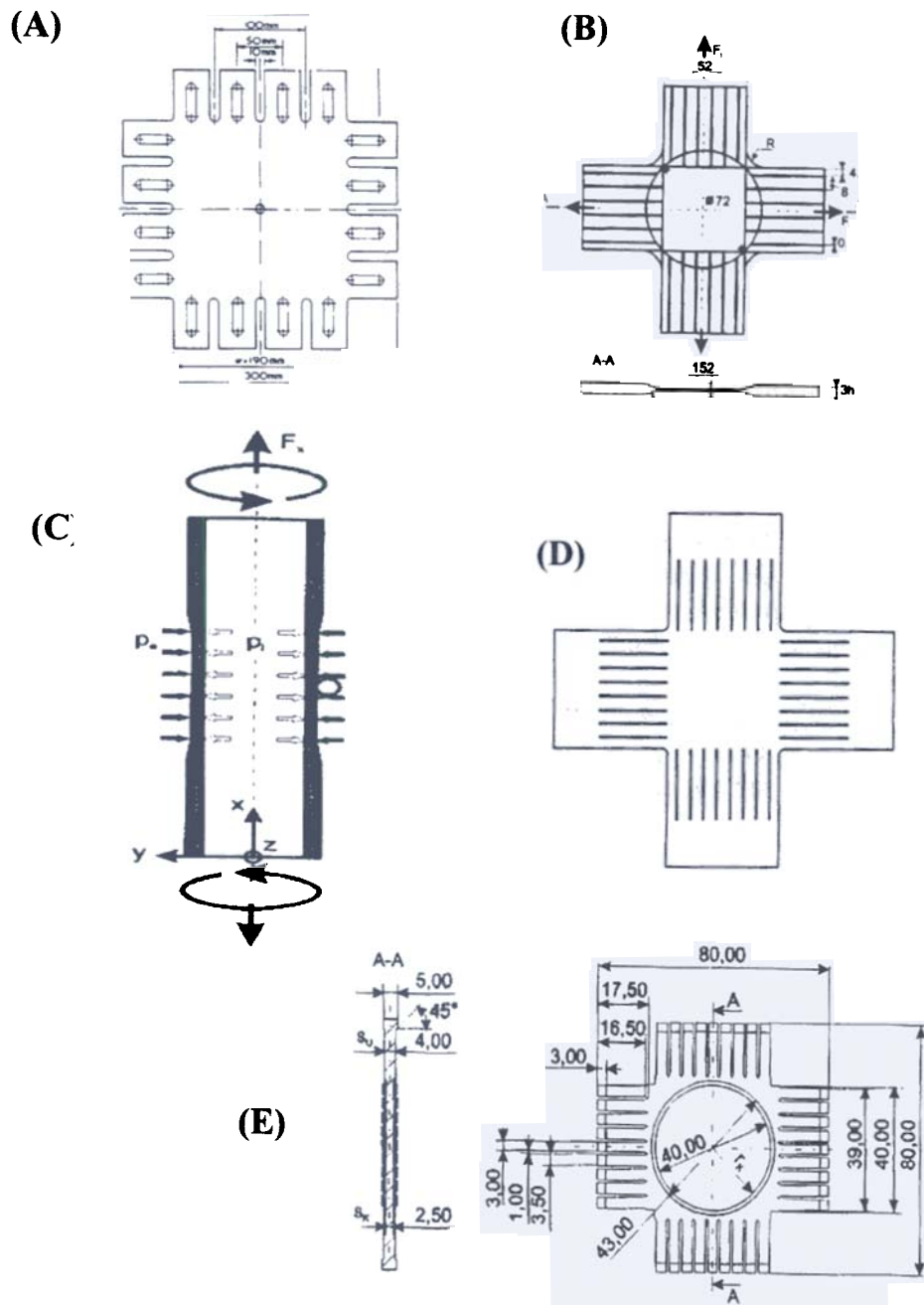


Figure Typical test geometries that have been used to measure stress-strain curves in biaxial tension. A: ref. 8, B: ref. 12, C: ref 5, D: ref 7, E: ref 3.

buckling of the specimen can be a problem and such specimens are difficult and expensive to machine from plastics.

1.1.3 Cruciform plates

The open literature contains numerous examples of cruciform specimen (Radon et al², Johnson¹², Monch and Galster⁷, Leever et al⁸), some of which are shown in Figure 1. The differences between these specimens that are nominally the same shape are in the overall dimensions, the size and number of legs, the thickness of the central region and the radius of the intersection between sets of legs on adjacent sides. The final geometry of the testpiece is tailored by finite element calculations to reflect the purpose of the test.

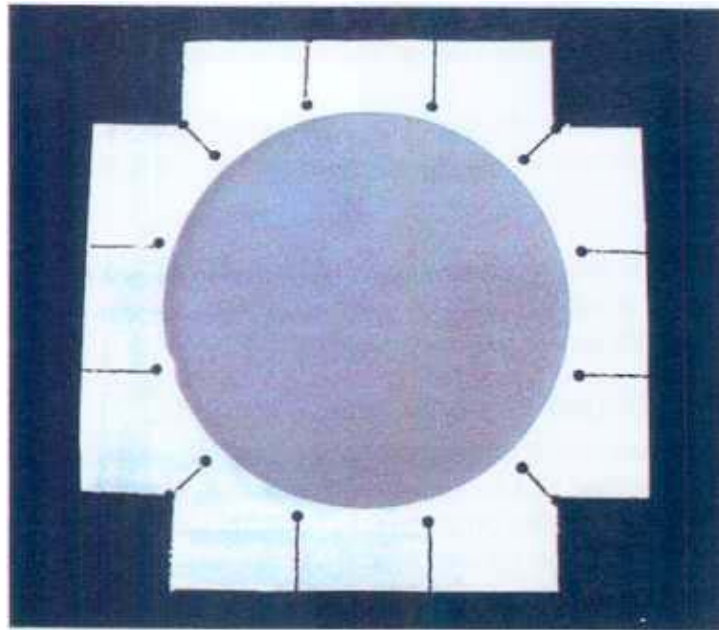


Figure 2 A moulded cruciform propylene-ethylene copolymer testpiece from the University of Leeds.

1.1.4 Clamping arrangements

The edge length of both film and cruciform specimens increases during testing. This lateral movement of the testpiece during the test has to be accommodated either by careful design of the testpiece or the clamping arrangement. Lateral movement of the testpiece can be accommodated by designing a cruciform specimen with 'legs' as shown in Figure 1(A,B,D and E) which deform during the test. The capacity of the cantilever legs to accommodate the increase in sample size can be enhanced by maximising the ratio of their cross sectional area to length. In practice this ratio is limited to the stress that each leg is able to sustain without significant plastic deformation or failure.

Additional lateral movement of the sample can be accommodated by clamping testpieces in 'whipple tree' loading shackles. Figure 2 shows a cruciform specimen developed by Sweeney et al at the University of Leeds^{4,6}. This testpiece has been specifically designed to measure the stress strain performance of film like materials at high draw ratios. The lateral deformation of the testpiece that takes place during the test period is accommodated by the loading shackle.

EXPERIMENTAL

2.1 MATERIALS

The two thermoplastics studied in this project are an acrylonitrile-butadiene-styrene copolymer (ABS, BASF, Terluran 967K) and a propylene-ethylene copolymer (BASF, Novolen 2300LL). The latter copolymer contains 8% ethylene. Both materials were supplied as pellets and either compression or injection moulded to form testpieces.

2.2 TEST EQUIPMENT

There are very few examples of commercially available machines to measure biaxial stress-strain curves and most published data has been generated using purpose built rigs. The two biaxial machines that were utilised in this project are based at the Universities of Essen (Germany) and Leeds (UK). These machines although similar in design have different clamping arrangements, specimen design requirements and method of operation.

Both test rigs stretch cruciform specimens at a prescribed rate via crossheads set at 90° to each other. Load cells positioned within the loading chain monitor the load applied as a function of time.

A brief description the specimen geometry and manufacture, clamping arrangement and mode of operation of the machines is given below, further details can be found in references Wanders³ and Sweeney et al⁴.

2.3 SPECIMEN GEOMETRY AND MANUFACTURE

Traditionally testpieces are machined from compression moulded or cast sheets of plastic. Testpieces produced using this route although relatively slow and expensive to manufacture are usually isotropic. This latter property can be advantageous from a modelling point of view but it may not represent the anisotropy commonly observed in molded articles i.e crates. Testpieces that mimic the degree of molecular orientation i.e. anisotropy characteristic of moulded articles can be manufactured by injection moulding. However such testpieces because of their geometry can suffer from excessive levels of molecular orientation when compared with that observed in 'real' complex geometry mouldings.

Two cruciform designs have been used to manufacture testpieces for this investigation. These designs are shown in Figures 2 and 3 and discussed in greater detail in sections 2.3.1 and 2.3.2.

2.3.1 University of Leeds

Thick films of propylene-ethylene copolymer for the University of Leeds biaxial testing machine were compression moulded from a purpose built mould using the conditions listed in Table 1. After compression moulding the testpieces were quenched into water at 20 °C and left to cool for a period of at least five minutes. The testpieces are moulded as squares with a waisted circular central region as shown in Figure 2. The twelve 'legs' of the testpiece are manufactured from the outer rim of the specimen by using a combination of drilling and cutting.

The width to thickness ratio of the legs severely limits their ability to accommodate lateral movement during testing which is instead carried out by movement of the clamp.

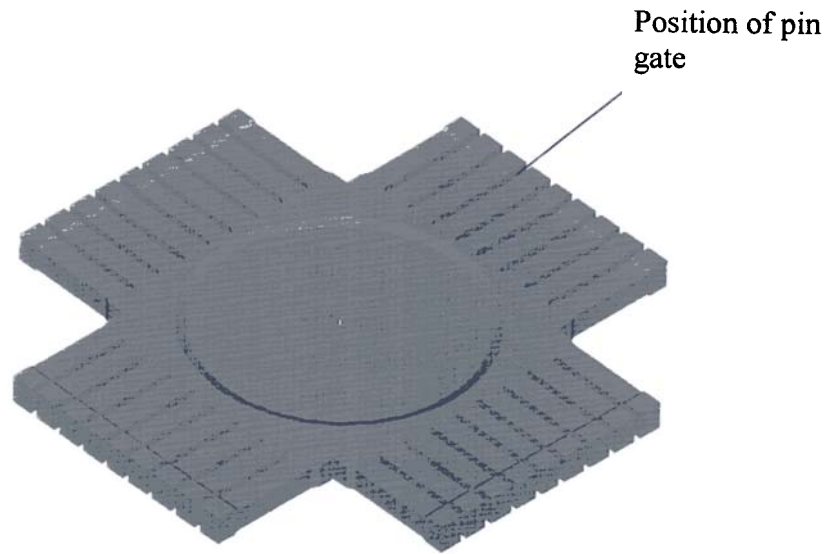


Figure 3 : Testpieces for the University of Essen biaxial stretcher were manufactured by injection moulding through a pin gate.

<i>Processing step</i>	<i>Processing details</i>
Mould temperature	220 °C
Moulding time	approximately 4 minutes
Cooling	rapid quench into water at 20 °C

Table Compression moulding conditions for propylene-ethylene copolymer

Further details of the specimen design and method of manufacture can be found in reference 4 (Sweeney).

2.3.2 University of Essen

Cruciform specimens of the type shown in Figure 3 were manufactured by injection moulding into a pin gated twin specimen mould. Details of the processing conditions used for both ABS and propylene-ethylene copolymer are given in Table 2. Details of the mould design may be found in reference 3 (Wanders).

The design of the central region of the testpiece is very similar to that of the Leeds specimen i.e. it is waisted to encourage localised deformation. However an important difference between the two designs is that the University of Essen testpiece requires no additional machining prior to being tested. The angle of the slope formed between the thicker outer rim and the central waisted region is 45°. The nine legs along each edge have a square cross-section and a length to width ratio of 4.4. The free edge of the legs are thickened to provide a catch point for the L shaped clamps that are used to mount the testpiece in the test rig (Figure 4). Care was taken to mount the sample in the test rig in the same orientation each time to

circumvent any variability in the data that could be attributed to anisotropy caused by using a single pin gate mould. Finite element analysis was used to design the testpiece and details of the analysis can be found in reference 3 (Wanders).

<i>Moulding conditions</i>	Material	
	<i>ABS</i>	<i>Propylene-ethylene copolymer</i>
Melt temperature (°C)	250	280
Mould temperature (°C)	55	55
Injection speed (mm s ⁻¹)	25	30
Holding pressure (Bar)	800	900
Holding time (s)	28	30
Cooling time (s)	30	35

Table 2: Injection moulding parameters used to mould cruciform specimens

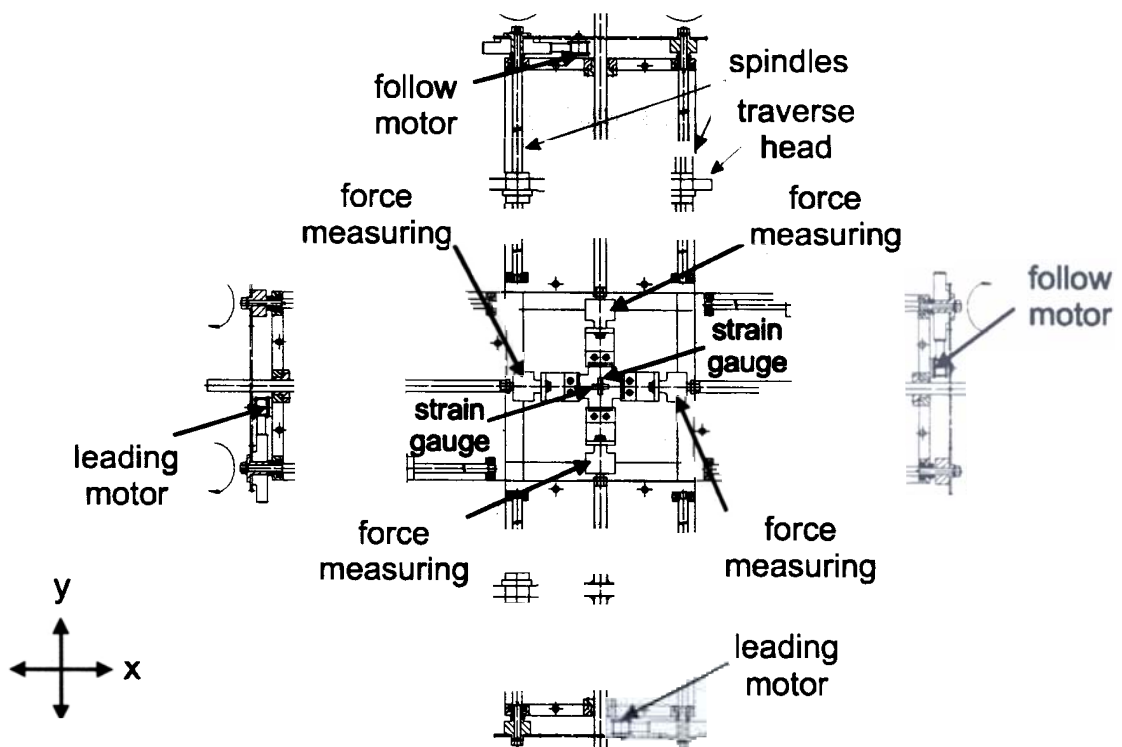


Figure 4: A schematic representation of the University of Essen biaxial stretching equipment. The cruciform testpiece is located at the centre of the device.

2.4 STRAIN MEASUREMENT

2.4.1 University of Leeds

A rectangular grid is printed on to the surface of the test specimen via a computer controlled printer equipped with a suitable pen that will write a durable relatively high contrast image on to its surface. A video extensometer (Messphysik ME64) was used to measure the tensile

strain that developed in the test piece during the test simultaneously in two directions. With this method, a video camera with a zoom lens attached is used to feed an image of the printed grid to a computer. Appropriate software is used to monitor the distance in terms of pixel elements between specific pairs of lines printed on to the specimen surface that serve as gauge marks. This distance is logged as a function of time. The software is capable of monitoring the distance between a number of marks that can be positioned along different axes. Sample deformation was determined over the central region of the test piece and subsequently converted to strain.

2.4.2 University of Essen

The deformation that occurred in the central region of the cruciform testpiece was measured using a biaxial strain gauge (HBM 6/120XY93) as shown in Figure 5(1). A cyanoacrylate adhesive was used to attach the strain gauges to the specimens. Problems were experienced in obtaining good adhesion between the strain gauges and the propylene ethylene copolymer. To some extent these were overcome by providing a clean keyed surface for the adhesive to adhere to and by using an initiator for the cyanoacrylate. Whilst strain gauges provide a convenient method for measuring strain particularly for cruciform testpieces they do locally stiffen compliant materials and therefore tend to underestimate the true strain developed in the sample for any given load. This issue is further discussed in Sections 3.3 and 3.4.

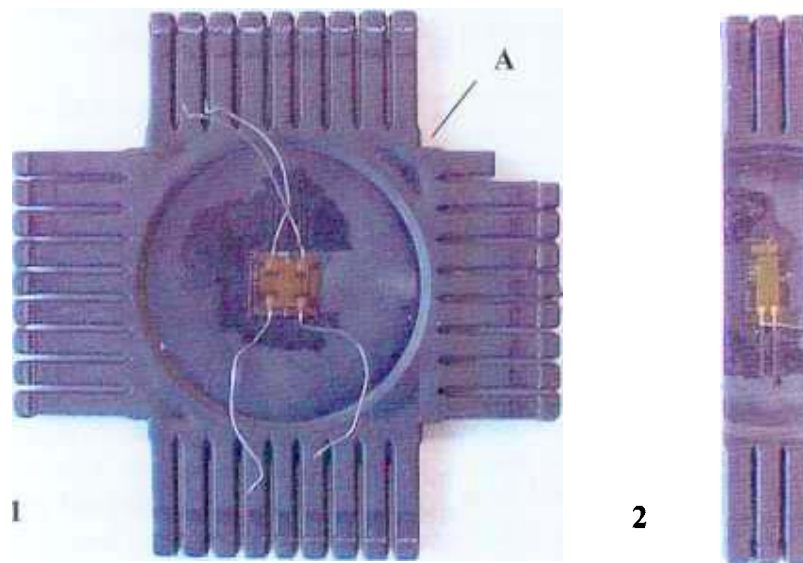


Figure 5 : ABS testpieces for biaxial (1) and uniaxial (2) tests showing the location of the strain gauges and the point of failure (A) for the biaxial test.

2.5 CONTROL OF STRAIN RATE

2.5.1 University of Leeds

Video extensometry provides a convenient non-contacting method for monitoring sample deformation and could be used to control the strain rate. However this is not possible in the

current configuration of the apparatus so that the rate of sample deformation was controlled by movement of the respective cross-heads.

2.5.2 University of Essen

The output from the biaxial strain gauge was used to control the rate at which the testpiece was deformed. This enables the rate of deformation of the sample lying beneath the strain gauge to be precisely controlled.

RESULTS AND DISCUSSION

3 UNIVERSITY OF LEEDS

3.1.1 Propylene-ethylene copolymer

The University of Leeds biaxial stretching machine applies a load to the arms of the specimen at a prescribed rate. This stretching machine performs well for low stiffness materials as shown in Figure 6(A) where the testpiece is uniformly stretched according to the peripheral dimensions. However within the testpiece there are signs of localised plasticisation as shown by uneven regions of the printed grid pattern. In contrast the testpiece deformed at room temperature, shown in Figure 6(B), has regions of stress whitening. These are positioned along the diagonals of the testpiece and at the junction of the rim and the waisted section where rupturing has occurred. This behaviour suggests that the biaxial stretching rig is inappropriate for obtaining stress-strain curves at room temperature.

Control of tearing or plasticization of the sensitive corner areas could not be controlled by changing the crosshead speed or the thickness of the testpiece.

3.2 UNIVERSITY OF ESSEN

3.2.1 ABS

3.2.1.1 *Assessment of anisotropy.*

The isotropy of the biaxial specimens was assessed at the University of Essen by determining the stress-strain curves in uniaxial tension for rectangular testpieces machined at 90° to each other from different cruciforms. The nominal dimensions of the uniaxial testpieces shown with strain gauges in Figure 5(2) were 12.5 mm x 2.5 mm x 78 mm. Figure 7 shows a typical set of stress strain curves obtained from specimens cut both parallel and perpendicular to the leg containing the pin gate. It is apparent from this figure that the testpieces are isotropic as the strains measured in samples cut in directions parallel and perpendicular to the flow direction are in good agreement. The stress-strain curve in uniaxial tension is linear up to strains of about 0.5% and shows considerable plastic deformation at strains in excess of approximately 2.5%. Young's modulus determined from these data is 2.48 GPa.

3.2.1.2 *Stress-strain curves in biaxial tension.*

Figure 7 shows an example of the strain response to an applied biaxial stress measured at a strain rate of $0.12\% \text{min}^{-1}$. The stress-strain curves measured in biaxial tension (University of Essen) are linear for strains below approximately 0.4%. All of the cruciform specimens failed when the strain exceeded 0.8%. The point of failure occurred in the same supporting leg in each of the specimens tested as shown in Figure 5(1), at which time the test was terminated.

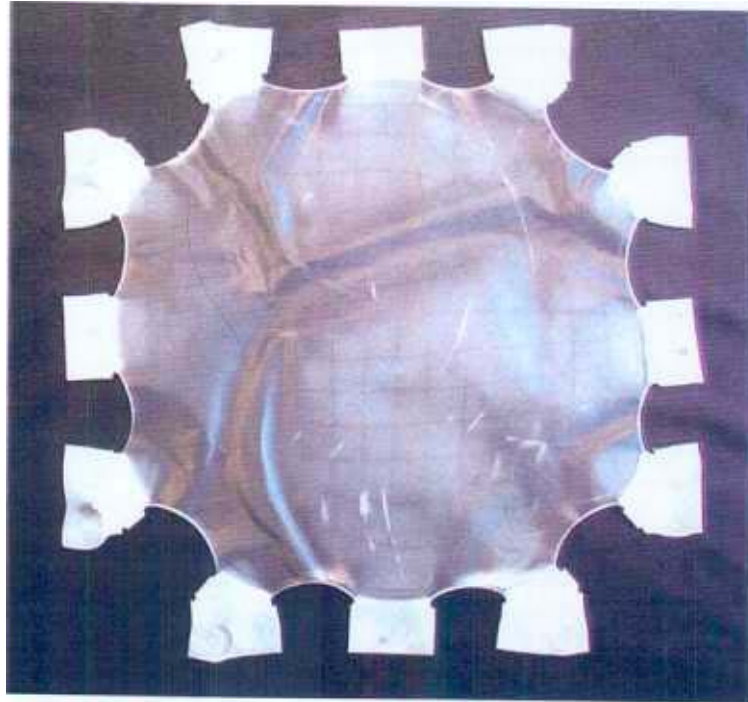
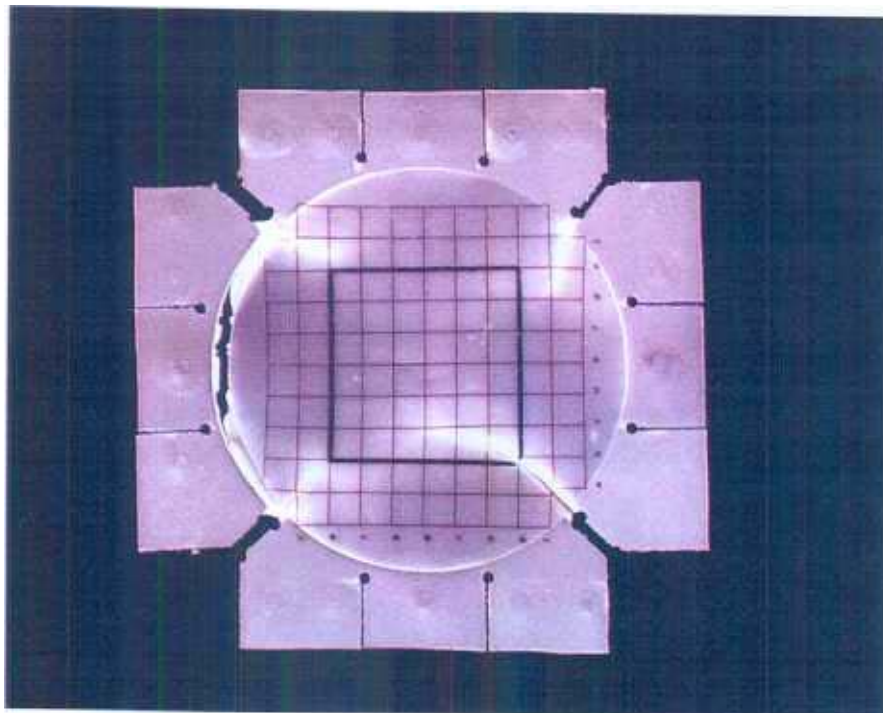
A**B**

Figure 6 (A) Biaxially stretching a polypropylene cruciform testpiece shown in Figure 2 at elevated temperature results in a relatively uniformly stretched specimen. However some localised distortion does occur causing buckling of the sample in the absence of an applied stress (This specimen was kindly provided by the University of Leeds). In contrast the ethylene-propylene copolymer testpiece tested at room temperature shows excessive stress whitening along its diagonals and at the junction of the rim with the waisted section (B).

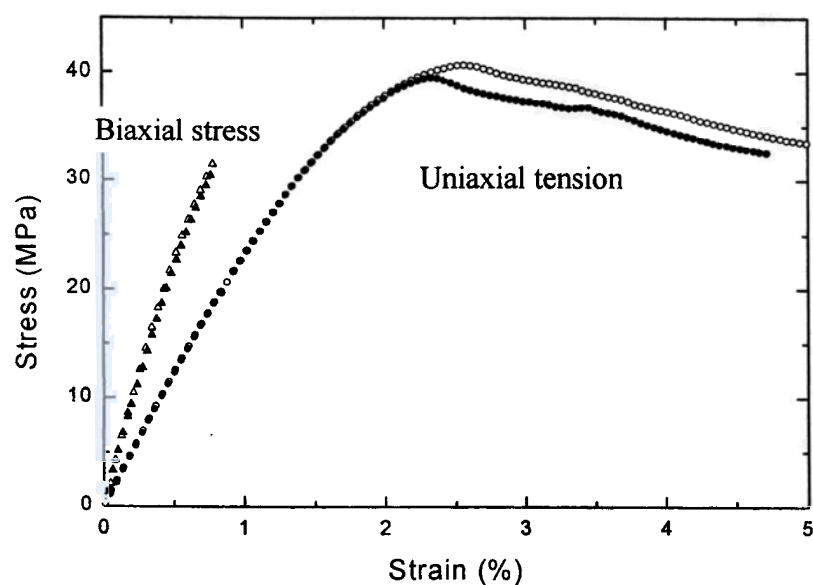


Figure 7 A comparison of stress – strain curves measured in uniaxial and biaxial tension at a strain rate of $0.12\% \text{ min}^{-1}$ for ABS at the University of Essen. Note that some points have been omitted to improve the clarity of the plots. Uniaxial :- measured perpendicular (○) and parallel (●) to the flow direction respectively. Biaxial :- measured perpendicular (△) and parallel (▲) to the flow direction respectively.



Figure 8 Reducing the thickness of the central region by 50% caused ABS samples to split as shown.

Attempts were made to extend the accessible strain range of the testpieces by thinning the central region of the cruciform specimen by 50 %. This was achieved by machining testpieces from both top and bottom faces to preserve the alignment of the central region with the load

cells. During testing at a strain rate of $0.12\% \text{min}^{-1}$ the samples failed by splitting as shown in Figure 8, despite care being taken to avoid sharp junctions being formed between the rim and the central region.

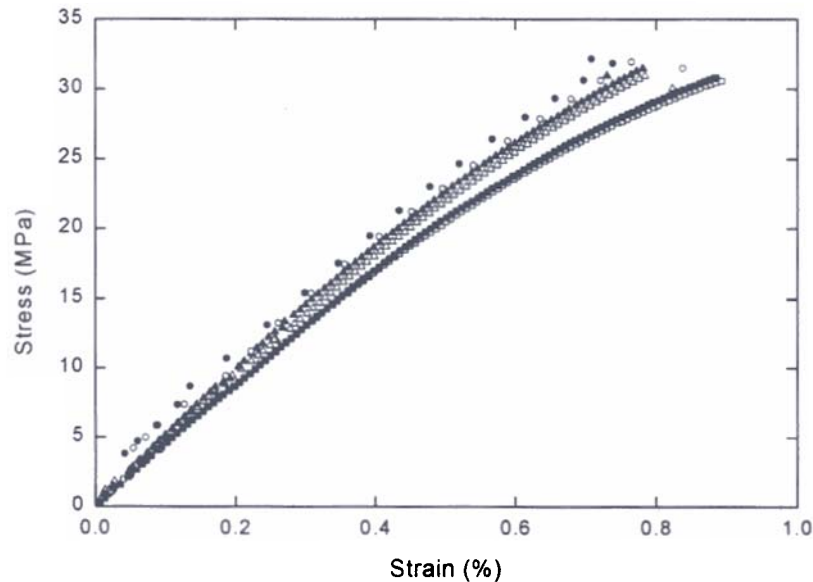


Figure 9 : Stress – strain curves for ABS measured at different strain rates.

Strain rate : $0.02\% \text{min}^{-1}$ ($\square$ = parallel, $\blacksquare$ = perpendicular)
 $0.12\% \text{min}^{-1}$ ($\triangle$ = parallel, $\blacktriangle$ = perpendicular)
 $1.2\% \text{min}^{-1}$ ($\circ$ = parallel, $\bullet$ = perpendicular).

It is possible that using a strain rate of $0.12\% \text{min}^{-1}$ causes the biaxial testpieces to fail prematurely. Figure 9 shows the effect of using both slower and faster rates of strain to deform the testpiece. From these results it is evident that increasing the strain rate moves the stress-strain curve to the left but appears to have no effect on the strain at which the samples fail.

3.2.2 Propylene-ethylene copolymer

A plot of biaxial stress versus strain for the propylene-ethylene copolymer is shown in Figure 10. These data were obtained at a strain rate of $0.12\% \text{min}^{-1}$. From this figure it is evident that a significant amount of plastic deformation within the central region of the testpiece can be measured. Premature termination of the stress – strain curve occurred when the strain gauges peeled away from the surface of the propylene-ethylene copolymer. This delamination occurred at strain levels well within the capability of the strain gauge indicating that the bond between the gauges and the propylene-ethylene copolymer needs to be improved.

Figure 10 shows that the propylene-ethylene copolymer undergoes significant plastic deformation at strains in excess of approximately 0.4%, at lower strains it is probably showing linear viscoelastic behaviour. Figure 11 shows a comparison of the biaxial data with a uniaxial stress-strain curve measured at a strain rate of $2.1\% \text{min}^{-1}$ using a video extensometer at the National Physical Laboratory.

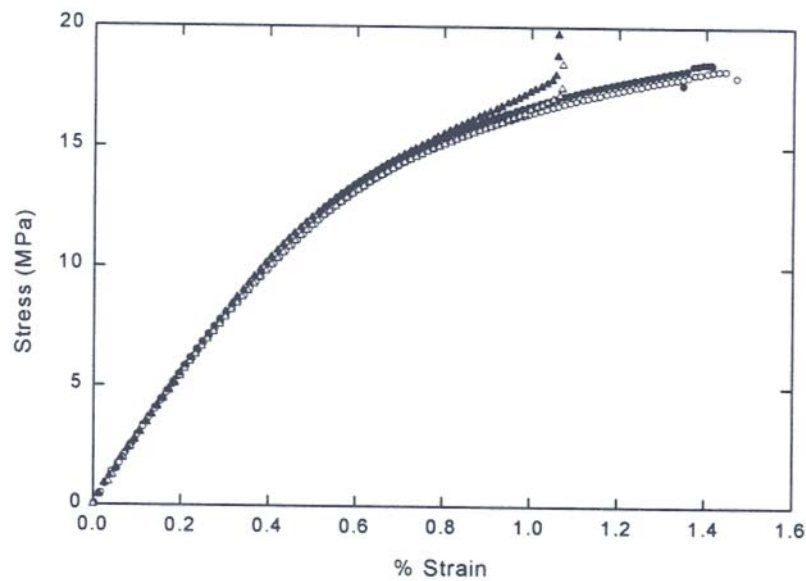


Figure 10 : Biaxial stress – strain curves for two specimens of propylene-ethylene copolymer. The open symbols represent strains measured parallel to the leg containing the pin gate. The filled symbols refer to data measured perpendicular to the direction of the pin gated leg.

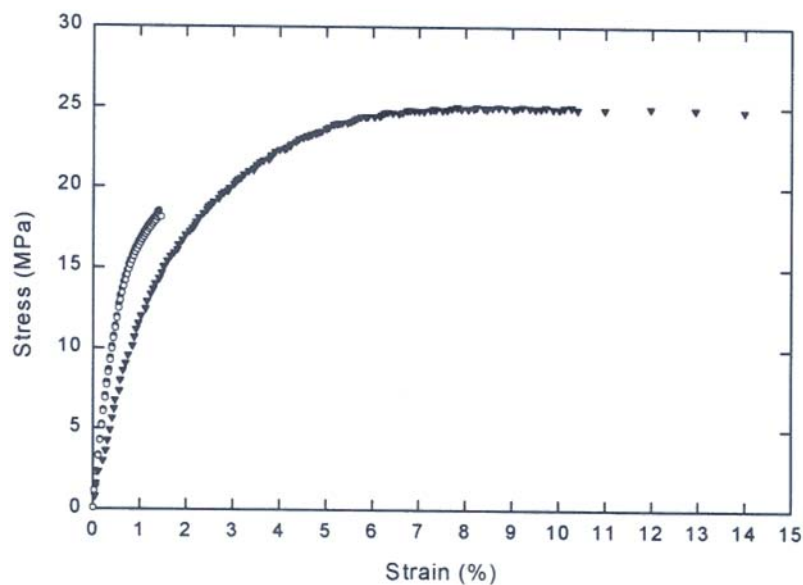


Figure 11: A comparison of the stress-strain behaviour measured in uniaxial tension of propylene-ethylene copolymer at a strain rate of $2.1 \text{ \%min}^{-1}$ at the NPL with those measured in biaxial tension at a rate of $0.12 \text{ \%min}^{-1}$ (○ = measured in a direction parallel with the pin-gated leg, ● measured perpendicular to the pin-gated leg) at the University of Essen. The NPL uniaxial strain data was measured using a non-contacting video extensometer whereas the Essen biaxial strain data was obtained from a strain gauge.

3.3 PROBLEMS WITH MEASURING STRAIN

Most strain gauges are designed to measure strains of 5% or less and they are mounted on to a relatively stiff polyimide backing film that can locally stiffen the sample (Duncan¹³). This stiffening effect introduces a measurement error in determining the materials response to an applied stress. The magnitude of the effect will depend on the relative stiffness of the gauge with respect to that of the testpiece but for materials such as acrylics ranges from approximately 4 to 16%, increasing as the testpiece thickness is reduced. At higher strains strain gauges have a tendency to become detached from the testpiece before the typical 5% strain measurement limit is reached. It should also be noted that strain gauges that have been specifically designed to measure strains approaching 10% can cause premature failure in dumbbell testpieces (Duncan¹³).

Monitoring sample deformation using non-contacting techniques overcomes any localised stiffening of the sample due to using strain gauges and considerably extends the range of strain that can be measured. The video extensometer used to monitor strain in the University of Leeds testpiece provides reliable data, particularly at higher strains where the signal to noise ratio is high.

3.4 STRESS DETERMINATION

Whilst it is relatively straightforward to measure the strain in the central region of cruciform specimens, determining the corresponding stresses is a significant problem. Calculating how the measured applied load is distributed within the testpiece requires finite element modelling techniques. Both of these approaches contain assumptions about the materials response to an applied stress. Finite element calculations made at the University of Essen assume a linear elastic response of the material to determine the scale factors that are used to convert applied loads into stresses (Wanders³). Each scaling factor describes a specific area on to which the external force is applied and depends on the materials Poisson's ratio (taken to be 0.4) but not its modulus. The Essen approach to modelling stress relies on there being a limited amount of deformation in the central zone of the testpiece where the strain gauge is located. This approach is valid providing that the load applied to the testpiece is controlled by feedback from the strain gauge. In the absence of strain control any localised plastic deformation of the testpiece that occurs is likely to cause localised relaxation of stretched material elsewhere and distortion in the stress-strain curve.

CONCLUSIONS

Measurement of the true stress / true strain curves under biaxial tension has not been successful in this project. The main problem is with the design of a test specimen that will allow the stress to be determined in the central (gauge) region of the specimen. For the purpose of evaluating elastic – plastic models, it is also necessary for the specimen to deform in this region to large strains (>0.1) without failure at stress concentrations elsewhere in the specimen.

The measurement of biaxial strain in the gauge region of the specimen is relatively straightforward using a video extensometer. Strain gauges are unsatisfactory.

5 ACKNOWLEDGEMENTS

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