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MACROMOLECULAR DIVISION
WORKING PARTY ON STRUCTURE AND PROPERTIES OF COMMERCIAL POLYMERS*

CHARACTERIZATION OF FINITE LENGTH COMPOSITES: PART I. INTRODUCTORY PAPER

(Technical Report)

The authors and contributing members dedicate this paper to their colleague and friend,
Professor Gerhard Zachmann

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Characterization of finite length fibre composites. Part I: Introductory paper (Technical Report)

Abstract: A project representing a sizeable effort of IUPAC Working Party 4.2.1 on two thermoplastic matrices reinforced with three different fibre types and involving two different injection techniques is introduced in terms of its objectives, adopted strategy, materials, main variables, outcome reporting and participating laboratories. This paper outlines details (constituents, composites, injection molding, mold cavity) common to all undertaken studies. At the same time it summarises the major outcome in terms of molding anisotropy and heterogeneity as both controlled by the constituting materials—matrix and fibre and processing conditions used for molding preparation. More detailed information which is contained in publications dedicated to individual areas under investigation, namely to:

(1) Mechanical performance of injected molded composites,
(2) Studies on thin sections extracted from moldings (wafers),
(3) Determination of structural aspects of composites,
(4) Modelling of stiffness and
(5) Rheological studies
is referred to in appropriate places.

1. INTRODUCTION

Over the last seven years a sizeable project has been conducted by members of IUPAC Working Party 4.2.1. The aim of the project has been to develop the basic understanding of discontinuous but 'long' fibre composites based on thermoplastic matrices and reinforced with different types of fibres. Mechanical and rheological performance of this material type, its relation to structural aspects which stem from different processing routes used and correlation of observed facts with available theories have been the activities in the focus of this effort.

The studied materials are selected in such a way that the role of all important variables known to control composite performance can be assessed. These are:

(1) the type of matrix:	polypropylene (PP) and Polyamide (PA)
(2) the nature of the fibre:	Glass (g), Carbon (c) and Kevlar (k)
(3) processing method	Classical injection molding and the so-called 'Multiple life-feed technique', both discussed below
(4) initial fibre length:	5 and 10 mm long pellets used as the feedstock for both processing methods

Composite performance mainly involves stress/strain behaviour under different deformation modes and at varying strain rates with full recognition of two important aspects of composite materials: (1) their anisotropy and (2) performance characteristics reflect the structural response of a specimen rather than the intrinsic properties of the material under investigation. For these reasons specimens are extracted from different parts of the molding and measurements are carried out with respect to all principal co-ordinates. The property variations through the thickness are determined by the examination of thin "wafers". Measurements of rheological parameters and quantification of relevant structural features, together with generation of clarifying data—often involving dedicated techniques novel to composites research—are conducted in parallel.

The following organisations participated in the programme:

Brunel University	London	UK
Shell Research	Arnhem	NL
Louvain-La-Neuve		B
Ausimont	Bollate	I
ICI	Wilton	UK
Nat. Res. Council	Montreal	CND
BP	Grangemouth	UK
Rhone-Poulenc	Saint Fons	F
University of Hamburg		D
DSM	Geleen	NL
Cranfield Inst. of Technology		UK
BASF	Ludwigshafen	D
Mobil	Edison, NJ	USA
Solvay	Brussels	B
Inst. Przem.Tworz. Farb	Gliwice	PL
Huls	Marl	D
DuPont	Wilmington	USA
Hoechst-Celanese	Summit	USA
Technical Univ.	Lyngby	DK
Hoechst AG	Frankfurt	D
University of Karlsruhe		D

When the nature of the project, with the involvement of a large number of active participants, had been taken into consideration, it was decided to report the work in six separate documents (Parts I–VI) which are linked by the common theme of 'Characterization of finite length fibre composites'. Considering this contribution to be the Part I, the other reports have addressed:

Part II:	Mechanical performance of injection molded composites (ref. 1)
Part III:	Studies on composite wafers (ref. 2)
Part IV:	Determination of structural aspects of composites (ref. 3)
Part V:	Modelling of stiffness (ref. 4)
Part VI:	Rheological studies of materials based on the polypropylene matrix (ref. 5)

Having introduced the project in terms of its goals, variables studied, participants, and the manner of reporting, the objective of this 'Introductory paper' is three-fold:

(i) to reveal the strategy of approaching the identified problems as adopted by project teams

(ii) to detail the aspects that are common to all of the parts in terms of the feedstock materials, processing routes, composite moldings, and

(iii) to highlight the major outcome in a format that provides a concise presentation of the full information contained in the cited papers.

2. ADOPTED STRATEGY

It has been well established (e.g. ref. 6,7), that properties of composites manufactured by injection molding are governed not only by the choice of constituents (matrix and fibre) and their relative concentrations but also by a number of parameters (temperature, shear stress, shape of the molding, its gating, etc.) that may be cumulatively called the processing conditions. Placing a particular system (matrix type, fibre type and length, matrix/fibre concentrations) in the hopper, flexibility in these processing conditions allows the injection molder to yield moldings that exhibit a different structural response in spite of an identical starting point. Fully acknowledging the fact that both the volume fraction and the 'reinforcing potential' of the fibres remain unaltered, the process generally results in:

(a) fibre fracture that reduces the initial length L_0, thus enhancing the overall number of fibres and inducing a distribution in the fibre length;

(b) fibre orientation φ in a given plane or fibre misalignment out of the plane θ with a possibility of vastly different orientation functions with respect to these angles (for definitions cf. Fig. 1) that, in addition, can be position dependent;

(c) anisotropy in properties when measured in different directions with respect to a defined co-ordinate system due to a variation in the structure1.

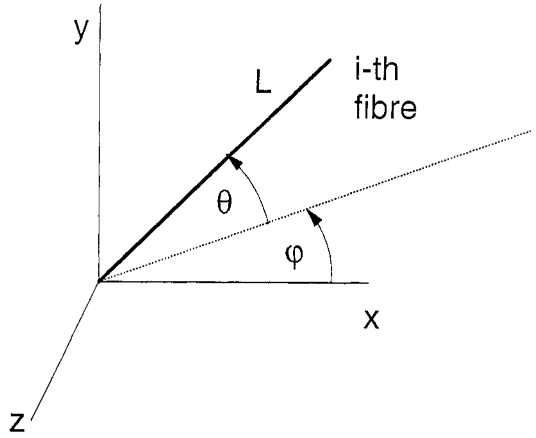

Fig. 1 Definition of angles describing fibre orientation

Working with the simplest type of moldings—a parallelepiped of length *D* measured in the direction *x*, width *W* defined in the direction *y* and overall thickness *T* in the direction *z*—(cf. Fig. 2) and keeping the fibre mass-fraction constant at 40 % , combinations of different thermoplastic matrix/fibre constituents, two different initial lengths of a fibre and, particularly, two diametrically different sets of processing conditions are deemed to produce different structures. These structures, different in their mechanical properties, will be relatable to the variables at stake via the structural characteristics fortified by additional information such as the rheological behaviour of heterogeneous melts and the interfacial behaviour between the matrix and the reinforcement.

Three types of reinforcement, two matrices, two initial fibre lengths and two processing routes allow 24 different composite structures to be manufactured and studied in principle. In order to restrict the number of sample conditions to a manageable level for the resources available to the project, the combinations of materials formulations and processing conditions have been restricted to the following (initial fibre length in mm identified by an integer):

Table I Composite types investigated

Fibre/Matrix	PP	PA
Carbon		10
Glass	5,10	5,10
Kevlar		10

To establish the "structure-property-processing" relationships for these twelve composites, the following steps have been taken:

(1) No attempt is made to quantify all the associated variables of the two manufacturing routes used. Thus we are using two simple adjectives, namely DYNAMIC to identify test pieces prepared by the multiple live-feed method (described in Section 3.31) and STATIC when referring to the outcome of the classical injection moldings operation (described in Section 3.32);

(2) Structural studies are conducted with the following objectives:

- to identify the form of distribution functions with respect to the fibre length and fibre orientation,
- to investigate the skin/core morphology (preferred planar orientation in the *z*-direction),
- to quantify any fluctuation in the fibre content with the *z*-coordinate and
- to describe the state of a matrix in terms of its degradation and orientation.

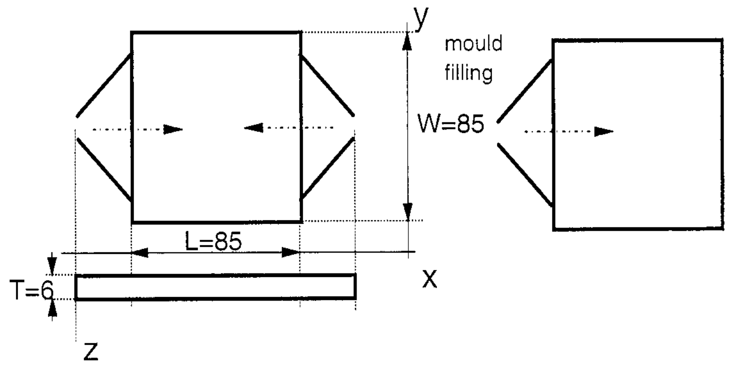

Fig. 2 Geometry and dimensions [mm] of moldings used

(3) Performance characterization is carried out by cutting moldings into prismatic bars either in the direction x coinciding with the melt flow and yielding the LONGITUDINAL properties or in the y-direction yielding the TRANSVERSE properties in the molding plane. These measurements involve specimens either of the same thickness as that of a molding (specimen position identified by either x or y co-ordinate) or much thinner 'wafers' further machined from the bars. Wafers allow mapping of properties not only with respect to x and y but also in the z-direction thus providing the through-thickness property profiles. It is understandable that different experimental approaches have been used for investigations of thin wafers and thick bars. Whilst for the former wafer stiffness measured by a non-destructive "rebound technique" (ref. 2) is the primary target, the whole spectrum of properties, in different deformation modes, at different strain rates and covering a wide temperature range has been generated for the latter (prismatic bars). Without implying that full property matrices are available for all materials studied, generation of the performance data (the modulus, ultimate stress and strain, lateral contraction ratio and Fracture Mechanics toughness characteristics) has been confined to the measurements under different (tensile, flexural, compressive and shear) deformations involving a span (creep → impact) of strain rates and a wide range (ambient → 160 °C) of temperatures.

(4) To relate experimental data to the existing theories describing the behaviour of composites both on the micro- and macro-mechanical level.

3. BACKGROUND TO ALL THE UNDERTAKEN INVESTIGATIONS

3.1 Composite nomenclature

The composite nature is described by the code of the XX/y N—MODE where:

XX denotes the matrix type—either polypropylene (PP) or polyamide (PA),
y denotes the type of fibre—either g (glass), c (carbon) or k (Kevlar),
N denotes the initial fibre length—either 5 or 10 mm and
MODE denotes the type of injection molding regime—either DYNAMIC or STATIC..

3.2 Feedstock

The novel 'Verton' type of reinforced thermoplastic matrices developed by ICI has been used. The composite precursor is obtained by melt impregnation of a reinforcement during pultrusion followed by chopping the extrudate into pellets of a given length (initial fibre length L_0). Whilst the fibre mass fraction has been kept constant for all composites at 40% , two initial lengths have been involved in the studies reported: 5 and 10 mm. The process is claimed to be associated with (1) a high level of fibre impregnation and (2) retention of a higher fibre length than those resulting from the injection molding of a blend containing a polymer powder and short fibres.

3.3 Molding operations

In total, six different compounds have been processed at the Wolfson Centre, Brunel University, Uxbridge into test plaques of the overall dimensions 85 x 85 x 6 mm (cf. Fig. 2) using the Dynamic and the Static processing mode for each matrix/fibre pair. The processing techniques used are described in the following two sections:

3.31 Dynamic processing mode

The multiple live-feed (MLF) injection molding process which has recently been developed at Brunel University is utilised in this project to produce the DYNAMIC injection molded plates.

The basic principle of the process, a full description of which has been in ref. 8, is to apply a macroscopic shear to the solidifying polymer melt in a mold cavity, with the objective of inducing favourable fibre orientation in the molding.

A schematic diagram of the equipment used in this work is shown in Fig. 3. The double live-feed molding device B is fixed as a heated extension to the conventional machine barrel A. The device contains two reciprocating pistons D and E which operate on the melt in the mold cavity via two separate nozzles and sprues to the mold C. A diagram of the cavity used in this study is shown in Figure 3. Each of the gates at the ends of the plate are connected to one of the nozzles of the double live-feed device. The mold cavity is filled from one of the end gates. This is achieved by programming one of the live-feed pistons to shut off one of the feed channels before the machine injects the melt. When the mold is full, the live-feed pistons are then reciprocated within their respective chambers with a phase difference of 180°. This operation is programmed to maintain a macroscopic shearing of the remaining molten material in the mold cavity until the whole section is frozen off. This ensures that the maximum fibre orientation possible by the process is produced in the plates. All of the molding cycles are monitored using a cavity pressure transducer which is situated at the centre of the plaque. More detailed processing conditions for this operation are given in section 3.4.

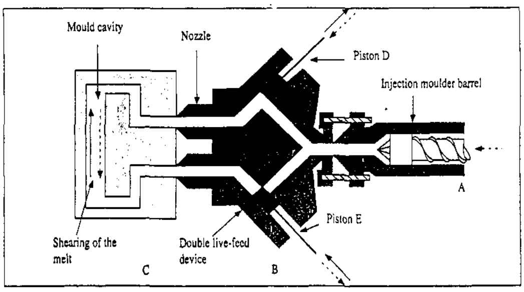

Fig. 3 Schematic illustration of the multiple live-feed injection molding (DYNAMIC mode).

3.32 Static processing mode

The classical injection process is carried out with one gate closed during the whole of the injection step. The melt is consolidated in the mold cavity by means of a conventional static hold pressure. The basic processing conditions (injection speed, temperature rate, etc.) have been the same as those used for the Dynamic molding—refer to the section 3.4.

3.33 Molding conditions

Table II details all conditions used for the six different composite types processed. The 'hold pressure' values refer to the hydraulic oil pressure set on the machine with the set polymer melt pressures being approximately 10-times these values.

In addition to the conditions given above, the following procedure has been adopted to minimise fibre fracture in all of the moldings:

(i) A low screw plasticisation speed of between 50 and 65 rpm used;
(ii) No plasticisation pressure set on the machine;

(iii) The gates and runners on the cavity equal in section thickness to the test piece (6 mm).

With respect to the Dynamic molding, the conditions are set so that the shearing action of the process is initiated immediately the mold cavity is filled. The mold temperatures used are higher than those used for the Static injection molding . Both of these actions are taken to reduce the thickness of the solid skin formed before initiating the shearing movements of the pistons.

The pressure on the live-feed pistons at the start of the process is set so that the maximum movement of the pistons is obtained. Subsequent stages are then set to ensure the solidification of the molding proceeds to completion with the shearing action being maintained throughout.

Table II Conditions used for processing of investigated composites

Conditions/System	PP/g 5,10	PA/g 5,10 PA/k 10	PA/c 10
Barrel temp. /°C	190–200	250–265	260–280
Mold temp./°C	70	150	290
MLF block temp./°C	200	280	290
MLF nozzles/°C	200	275	150
Hold Pressure/bar – Static	45	45	70
Hold Pressure/bar – Dynamic	11	10 bar for 6 s 25 bar for 12 s 36 bar for 70 s	12
Piston Freq./Hz	0.25	0.25	0.33

3.34 Visual observations

The mold filling characteristics of different composite types are assessed on the basis of short-shots moldings. Fig. 4 serves as an example of the situation for the PA/c 10—DYNAMIC composite type: The flow of the melt into the cavity is primarily down the centre from the gating point as shown in the left part of Fig. 4. As the melt front advances, a fold is formed as shown in the middle part of Fig. 4 and the front does not appear to expand in the width direction until it makes contact with the cavity wall. The fibre orientation in the plaques is expected to reflect this complicated mold-filling pattern by being strongly position dependent.

Concerning the PP/g 5,10 composites, moldings from the Dynamic processing have an appearance notably different from those made by the Static molding. As the former (the Dynamic) mode packs the mold more effectively than the latter, a contrast effect believed due to stress-whitening appears in the x-direction with a transparent streak present approximately half-way between the plaque edge and its longitudinal axis of symmetry. The intensity of the whitened area is believed to indicate the level of

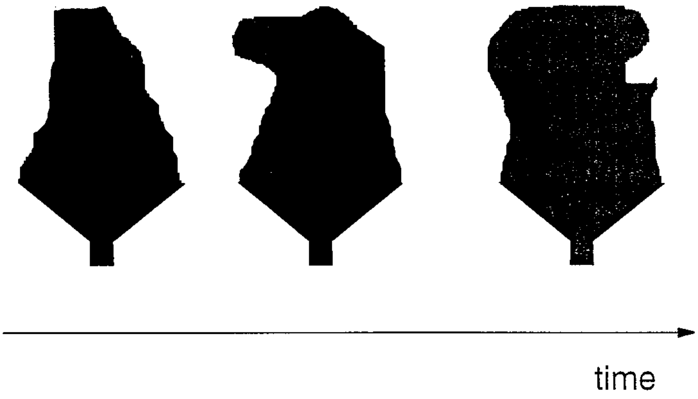

Fig. 4 Mold filling as a function of time—System: PA/c 10—DYNAMIC.

residual stresses with the more transparent region being associated with a minimum stress level. This feature correlates well with measuring the thickness profiles in the y-direction where the centre section (y=0) has been found to be approximately 0.07 mm thinner than the transparent streaks. Higher residual stresses are associated with the slight surface sinking at the centre which is also accompanied by the presence of stress whitening in the same region.

4. SUMMARY OF THE RESULTS

4.1 Composite structure

A paper (ref. 3) dedicated to the structural issues of the injection molding has addressed areas reflected by the headings of the following subsections. Its major outcome is a clear demonstration that both processing techniques lead to structurally complex moldings whose nature is closely related to the processing mode.

4.11 State of matrices

Both processing modes are associated with a slight polymer degradation in PP/g composites. The molecular weight averages M_w and M_z determined by gel permeation chromatography exhibit deficits of 15 and 40% respectively when comparing appropriate values obtained for the feedstock and the material extracted from a molding. The type of processing has not been found to have any effect on the degradation severity.

4.12 State of the reinforcement

4.121 Skin/core morphology The injection molding process is known to lead at least to a three-layered structure, with each layer appearing as a distinct entity associated with a particular fibre orientation, due to the fountain-flow mechanism (ref. 9). The actual nature of this morphology is dependent on the feedstock (the Verton type of material tends to exhibit more distinct skin/core structure than simple fibre/polymer powder blends) and the actual conditions of injection molding. Having deliberately processed by means of the two different processing regimes, structural aspects of the skin/core nature need to be addressed first. Microscopy of polished surfaces has clearly revealed (ref. 3) the multi-layered structure for the Dynamic injection molding with the layered structure in the PA/g and PP/g composites being further influenced by the matrix type (skin due to PA > skin due to PP) and the original length L_0. (skin for L_0=5 mm thicker than that L_0=10 mm). For PP/g composites processed by the Static injection molding and the system PA/c 10, the skin/morphology appears to be not so well defined. In addition, individual layers appear to contain different fibre concentrations with the core being richer in fibres than the skin regardless of the fibre. The morphology of this type for PA/k 10 has not been investigated.

4.122 Fibre length distribution The injection molding of long fibre composites is accompanied by a dramatic fibre attrition leading to a wide distribution with its first moment, defined as the number average fibre length L_n, being substantially lower than the original length L_0 contained in the feedstock. Concentrating on the composites reinforced with glass, distribution in fibre length appears to be insensitive to L_0, but depends strongly on the processing mode used and the type of matrix: The Dynamic mode leads to lower L_n values than the Static processing and the PA materials are found to have shorter glass fibres than those contained in the PP composites after processing.

Fibre fracture does not only induce a fibre length distribution $n(L)$ but also increases the number of fibre ends. These may be considered as potential defect sites (or stress concentrators) with consequences for a property such as composite toughness (Section 4.33).

The most narrow distribution and the lowest L_n values have been encountered in the PA/c 10 composite type.

4.123 Fibre orientation The profiles of orientation angles φ and θ in x-, y- and z-directions are generated by the statistical analysis of fibre images (ref. 10). Due to the amount of work involved, only PP/g 10 STATIC and PA/c 10 STATIC systems have been studied with the results confirming the structural features of composites already described: The core/skin morphology and its extent in the PP/g 10 STATIC composite is clearly demonstrated: The average value for θ is practically zero and independent of the z- and y-co-ordinates. Analysis of the angle φ shows that the fibre orientation in the skin region tends to be random and that in the core is preferentially oriented in the y-direction. Consistency in the angular profiles with respect to the x-direction indicates a relative structural homogeneity across the molding width.

Structural features of the PA/c 10 STATIC material are diametrically different and in line with observation from the mold filling process: Skin/core morphology is ill defined, there is a high concentration of fibres misaligned out of the molding plane and, most importantly, the y-profiles of the angles ϕ and θ vary appreciably with the x-direction. In very simple terms, one might contemplate describing the fibre orientation in this composite type as three-dimensionally random and highly heterogeneous throughout the molding.

4.2 Interfacial behaviour matrix/reinforcement

Each matrix/reinforcement combination possesses a unique interfacial bonding characteristic. Judging by the critical fibre length analysed by fractography of failed coupons, the interfacial strengths can be ranked in the order PA/c>PA/g>PP/g. This affinity gradient ties in with the average fibre length L_n characteristics and also with the overall amount of a matrix adhering to the surface of a given fibre as qualitatively (microscopy) observed.

4.3 Composite performance

On the basis of the structural information, composites are expected to be anisotropic. Whilst actual properties such as the stiffness, strength, impact resistance and the coefficient of thermal expansion are likely to be controlled by both the distribution in the fibre length and the fibre orientation, the level of anisotropy and its orientation can be anticipated to be governed by the processing mode.

Two papers deal with these aspects: Properties measured on full thickness (T=6 mm) specimens extracted from different parts of a molding are reported in ref. 1. A more detailed study carried out on thin 'wafers' and mapping property profiles in z-direction is contained in ref. 2.

4.31 Anisotropy

Regardless of the composite type, the Dynamic processing causes longitudinal properties to exceed transverse characteristics. The Static mode reverses the anisotropy orientation making the longitudinal response weaker. This is manifested without any exception and irrespective of the deformation mode (tension and compression) by the moduli E, lateral contraction ratio ν, ultimate strength σ_u, toughness characteristic K_Q (ref. 11) and coefficients of thermal expansion α. In the light of this information, the Dynamic processing mode appears to orient reinforcing fibres preferentially in the x- (melt flow) direction. Different composite types exhibit varying levels of anisotropy. Whilst a high level of anisotropy typifies PA/g and PP/g materials, that for PA/c and PA/k is developed to a less significant level.

4.32 Heterogeneity

A poor inter-laboratory agreement in quoted data and large standard deviations within intralaboratory data sets are in line with the structural characterization and indicate moldings to be heterogeneous. Heterogeneity most probably originates from either an unpredictable cavity filling for PA/c (proven) and PA/k (suspected) composites or from the skin/core morphology associated with the fibre orientation in the individual layers being position dependent. The latter statement holds for the PA/g and PP/g composites which consistently exhibit a lesser scatter in transverse properties than that observed for the longitudinal characteristics.

The PP/g composite, regardless of L_0, has been found to exhibit the stiffness profiles shown in Fig. 5. For both of the processing modes, the transverse modulus is x-independent as also found from the image analysis. The processing mode controls the stiffness profile in the y-direction as reflected by the longitudinal properties. Both injection molding processes lead to a parabolic profile with an extreme in the centre plane (y=0). Whilst the parabola shows a minimum for the Static processing, the maximum is exhibited when the Dynamic mode is used.

4.33 Properties of moldings

Apart from being dominated by the fibre orientation (and thus by the processing mode) the individual constituents are equally important: The fibre type dominates the stiffness, the matrix governs the ultimate strength. The stiffness can be ranked in the order c>k≈g, the strength and toughness are generally better for PA than for PP composites. Not surprisingly, the highest stiffness and strength are obtained for PA/c 10 measuring stiffness in the longitudinal direction of samples made by the Dynamic injection molding and the strength in the transverse direction of moldings manufactured in the Static mode. The same pattern also applies to composites of other types with the original fibre length L_0 playing an insignificant role.

Different values of the number average fibre length L_n (considered to be inversely proportional to the number of fibre ends) that typify the Dynamic and Static processing modes broadly correlate with the composite strength and toughness (ref. 1): Specimens produced by the Dynamic mode have lower values than their counterparts made by the Static mode.

A slight dependence of the tensile stiffness on the strain rate has been detected: Higher strain rate deformations yield expectedly higher stiffness values, however the matrix viscoelasticity is masked by the heterogeneity of composite structures. The presence of the skin/core morphology prevents an easy comparison of the flexural and the tensile properties.

The temperature effects observed are in line with the behaviour of thermoplastic matrices: Both the stiffness and the strength are decreasing functions of the temperature.

4.34 Wafer studies

Thin rectangular slices and circular discs prepared by the machining of prismatic sections or moldings respectively have allowed the composite performance to be assessed in the thickness direction and the structural features to be firmed up using simple techniques (radiography). Using the so called 'Rebound technique' (ref. 12), stiffness of thin rectangular slices cut in both principal directions from PP/g 5, PP/g 10 and PA/c 10—STATIC and DYNAMIC composites has been mapped as a general function of x, y and z. The situation for the PP/g 5 and 10—DYNAMIC and STATIC composites is given in Fig. 6: The highest modulus and thus the most perfect fibre alignment in the x-direction is attained in the skin composite layer $|Z| \rightarrow 0.5$ using the DYNAMIC mode for processing. At the same time, the lowest modulus is measured for the central wafer ($z=0$) extracted from the molding prepared under the Static regime and tested in the longitudinal direction. Simple micromechanical modelling (ref. 13) further discussed in section 4.4 indicates that these extreme stiffness values may be considered to be the true characteristics of the lamina reinforced by short fibres whose lengths conform to distributions established experimentally. For comparison, the theoretical values for stiffness in the longitudinal and transverse direction and the stiffness due to the planar, random fibre orientation stiffness are also given in Figs. 5 and 6.

The stiffness profiles given in Fig 6 are important for two further reasons: (a) They truly reflect the fibre orientation distribution established for PP/g 10 STATIC by the image analysis and (b) they indicate the likely type of layered structure in the PP/g—DYNAMIC moldings for which the image analysis,

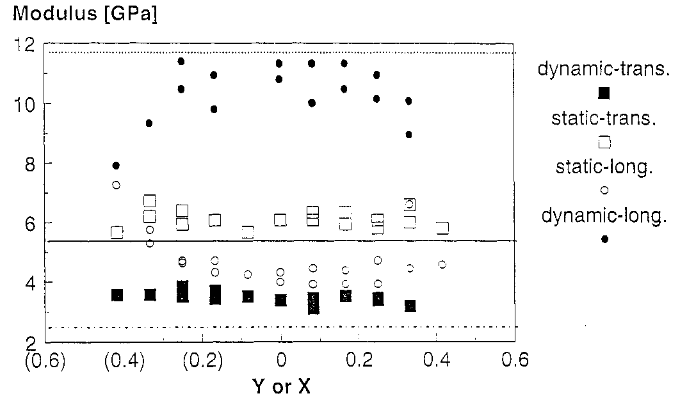

Fig. 5 Modulus variation in moldings, System: PP/g 5 and 10—directions X and Y (Micromechanical predictions shown for comparison: Longitudinal (dotted) and transverse (dashed) for the aligned fibres, isotropic modulus (solid) for the random planar orientation

unfortunately, has not been carried out: A high fibre alignment in the x-direction and in the skin regions abruptly changes in the core, i.e. the molding centre z=0 where the fibre orientation appears to be random. The relative insensitivity of the transverse stiffness to the z-coordinate indicates that the skin/core morphology is once more independent of the position in the x-direction.

With regard to the PA/c 10 composite, the rebound technique has given highly scattered stiffness data (irregular cavity filling) which prevents a similar analysis from being done for this composite type.

4.4 Modelling of measured values

Overlapping the information contained in sections 4.1 and 4.3, the composite performance has been shown to correlate well with structural features. The last remaining problem is to address how well existing micromechanical models can predict composite behaviour. This question is answered in ref. 4 devoted to modelling stiffness values measured in flexure and tension.

Using the micromechanical procedure based on the 'S-combining rule' (ref. 14), the elastic constants are derived from properties of isotropic constituents (modulus and lateral contraction ratio), their relative concentrations and the structural information on reinforcement. Here the distribution in the fibre length yields the average aspect ratio (L_n normalised on the fibre diameter) and the distribution in ϕ and θ angles provides in- and out-of-plane orientation functions. Equations describing deformation of a simple multi-layered beam have been used to derive flexural stiffness.

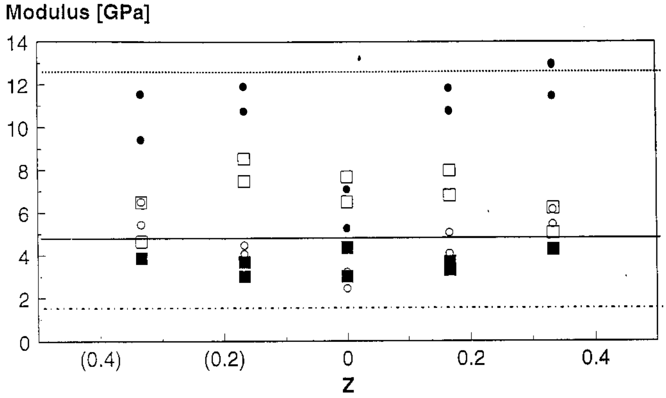

Fig. 6 Modulus variation in moldings—System: PP/g 10 (Central planes in z-direction) [Key to symbols the same as for Fig. 5]

Theory/experiment agreement can be summarised as reasonable with the fit assisted by the scatter in measured values due to the molding heterogeneity. However, with respect to the scope of structural details and the level of their sophistication, modelling must be seen more as a rationalisation of the observed—in the sense of both the performance and the structure—and less as an elegant substitute for experimental determination.

4.5 Rheological studies

With the effort entirely focused on PP/g 5 and PP/g 10 systems, the unfavourable feedstock geometry in relation to capillary rheometers has not been found to be an obstacle in generating reproducible interlaboratory characteristics. High Trouton ratios associated with extreme die entry-angle cones and recirculation zones typify long-fibre reinforced thermoplastics. Rheological measurements are marked by significant pressure fluctuations due to fibre rearrangement events leading to their reinforcement orientation and local variations in the local fibre concentration in the extrudate. Over a longer time scale, the die entry pressure drops can be viewed as a steady plateau.

The frequency of granule rearrangement (approximately one event per sec and at 100 s^{-1}) correlates well with extrudate velocity and pressure fluctuation data. Increasing shear rates result in a more pronounced inhomogeneity, a higher elastic fibre recovery in the extrudate and a greater pressure fluctuation.

In the oscillatory shear measurements, a high strain amplitude dependency and, consequently, a spread in data from different laboratories has been encountered. The data correlate well with squeeze flow measurements but show a poor relation to the capillary or steady shear rotation measurements. Fibre length dependent yield stress has been calculated by means of a modified Casson approach.

It has been confirmed that the material flows in an atypical fashion for injection molding composites. Flow is by 'domains' of small bundles of fibres (around 100). These domains, not only affect the flow behaviour, but must be considered in the ultimate morphology in molded parts, where this characteristic can still be identified.

5. CONCLUSIONS

- Simple plaques in the form suitable for testing and manufactured by an injection molding of the feedstock based on a finite-length fibre/thermoplastic are complicated structures. Their testing reveals less their 'material aspects' due to the constituents and their concentrations; it is more a complex response of a strongly anisotropic structure.
- The structural response is predominantly governed by the spatial distribution of reinforcing fibres which is dependent both on the molding route used and the fibre/matrix combination. A relatively simple skin/core morphology typifies the PP/g composites which contrast with a more complex structure of the PA/c moldings.
- Two manufacturing routes investigated, namely the STATIC (classical injection molding) and the DYNAMIC (multiple live-feed injection) have been found to cause a significant fibre attrition and to result in different fibre orientations: Whilst the Dynamic mode orients fibres (melt flow direction) in the skin regions near the mold surfaces, the Static mode results in transverse orientation to the melt flow in the central core region.
- The structural features of composites correlate with the performance of moldings. As a result, elastic constants of a lamina reinforced with short-length fibres, can be extracted from the structural response.
- Mechanical performance can be related to the structural features of composites, i.e. to properties of constituents, their concentration and the distribution functions describing the fibre length and fibre orientation, by means of micromechanical models.
- The rheological studies are inseparable from the solid-phase behaviour of composite structures manufactured by injection molding.

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