Microstructure–property relationships of GRP

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Fibre-reinforced composite materials are being used increasingly in critical applications, when the primary function of the material is to support loads, but very high safety margins are commonly used for such applications. Such large safety margins arise from the uncertainties regarding the mechanical behaviour of composite materials. The authors believe that the lack of microstructural definition of composite materials may make a substantial contribution to these uncertainties. In this initial study, relationships are sought between microstructure and properties of a model microstructure. The methods used are applicable to a very wide range of composite materials.

1. Introduction

Composite materials are being used increasingly in applications where a precise prediction of the mechanical behaviour of the material is essential. Glass-reinforced plastics have become well accepted for applications in which load-bearing ability is not particularly critical; examples of such applications include the hulls of small boats and yachts, the front nose section of the B.R. 125 high speed train and the body-work, including replacement components, of motor vehicles. The lack of precise knowledge regarding the mechanical behaviour of composite materials is, however, illustrated by the very high safety margins applied when the primary function of the material is to support loads; examples of such applications include the hull of the Royal Navy’s experimental mine-hunter, H.M.S. Wilton, and the Central Electricity Generating Board’s box for cooling water at power stations [1, 2]. A safety margin of around 20 is commonly used for such applications; the comparable safety margin for structural steel is often around 5. However, economic factors and required strength/weight ratios are increasingly making the use of such high safety margins for reinforced plastics unrealistic. Increasingly then, the mechanical behaviour of composite materials must be better specified.

The reasons for the uncertainties regarding the mechanical behaviour of composite materials may be divided into two broad areas. The first concerns the lack of knowledge regarding failure mechanisms in composite materials; an understanding of such mechanisms is particularly important for the prediction of the long term behaviour of composite materials including, for example, environmental degradation and fatigue behaviour. Considerable research effort is presently being applied to the elucidation of failure mechanisms. Non-destructive tests are being developed both for the monitoring of small test pieces and for the monitoring of large structures during proof tests. These non-destructive test methods include acoustic emission monitoring, and other methods for the detection of existing or growing flaws, such as ultrasonic testing and vibration testing (e.g. [3–5]). The second reason for the uncertainties regarding the mechanical behaviour of composite materials is the lack of consistency in mechanical test results from specimens which are considered identical in terms of the usual description of composite materials.

The usual description of fibre composite materials consists of a specification of the type of matrix and fibres, the volume fraction occupied by, and the orientation of, the fibres. No information regarding the fibre sizes or their distribution in the matrix is given normally. Thus, materials which are considered identical in terms of the
usual description may have very different microstructures. It is postulated that the inconsistencies found in the mechanical behaviour of apparently identical test specimens may frequently be explicable in terms of different microstructures. A quantitative definition of the microstructure of composite materials is, therefore, essential to allow reliable use of these materials in critical applications.

In the present study, the aim has been to establish methods by which relationships between microstructure and properties may be established. Further, the extent to which these relationships may be quantified has been sought and in order to achieve this it has been necessary to confine this initial study to a model microstructure.

Methods have been developed and described for producing a quantitative description of such microstructures and for specifying its statistical homogeneity [6]. This method depends on acquiring large amounts of data using an image analysing computer (a Quantimet 720 in this case) from unidirectional glass-fibre reinforced polyester resin composites. The methods of microstructural definition are not, however, restricted to this particular composite material. The methods could be applied to any volume fraction at any scale; steel-reinforced concrete could, for example, be examined using reduced photographs. The methods could easily be extended to include the distribution of a further phase, for example gas bubbles or a different type of fibre as in hybrid composites. The shape classification available on the Quantimet means that the methods could be extended to the examination of multi-directional materials; the principal axes would be examined separately and the fibre orientation would simultaneously be measured. The gross inhomogeneities in commercial hand lay-up glass-reinforced polyester resin are probably too marked for direct application of the methods. However, it may be possible to modify the methods, for example by using a coarser measurement grid, to allow some quantitative description of the microstructures of these commercially produced materials.

The ultimate aim of the application of quantitative microscopy to composite materials is the derivation of bounds of acceptable microstructures for the materials to be suitable for a particular application. The first step must, therefore, be the correlation of microstructural parameters with mechanical properties. The bounds of acceptable mechanical properties for a given application must be derived, both from theoretical considerations and experimental measurements. Such experimental measurements would include the non-destructive test methods developed for the elucidation of fracture mechanisms described above. The two steps could then be combined to allow the statement of acceptable bounds for microstructural parameters for the given application. The initial stage of this correlation, namely the correlation of microstructural parameters with mechanical properties, is discussed in this paper. The material considered is unidirectional glass fibre-reinforced polyester resin, but, as discussed above, the approach and analyses are not restricted to this particular composite material.

2. Experimental details
The experimental procedures adopted in this study are summarized here while a fuller description of them may be found in [7].

2.1. Material and section preparation
Unidirectional beams of glass fibre-reinforced polyester resin were prepared in the laboratory using a pre-impregnation technique. The fibres were all oriented parallel to the long axis of the beam. Glass fibres in tows, that is bundles containing around 10,000 fibres, were clamped in a frame and impregnated with polyester resin. The impregnated tows were laid up in successive layers in an open-ended mould. The mould was pressed, and some dispersion of the tows occurred and the excess resin was expelled from the open ends of the mould. The mould was left overnight for the resin to cure, and the finished beams were then removed. Typical beam dimensions were 250 mm x 12 mm x 10 mm; the volume fraction occupied by the fibres was about 20%.

Sections for microstructural examination were cut perpendicular to the long axis of the beam; that is perpendicular to the fibre direction. The sections were mounted in cold-setting mounting resin and pre-ground before they were diamond polished. On completion of polishing the glass fibres were barely distinguishable from the resin (Fig. 1a). However, contrast was enhanced markedly by the use of Nomarski interference indicating that the resin had been removed preferentially (Fig. 1b). It was found possible to preferentially etch the interface between the fibre