WASC 2257

Article on
Short Fibre
Reinforcement
'Whiskers'
New Technology
No. 46
May 1971

new technology

NUMBER 46: MAY 1971

DEPARTMENT OF TRADE AND INDUSTRY

New Technology and *Trade and Industry*

As already announced, *New Technology* will cease as a separate publication, distributed free, after the June 1971 issue. *New Technology* will then be published as a monthly supplement to the Department of Trade and Industry's weekly journal, *Trade and Industry*. Readers who wish to continue to receive *New Technology* after June 1971 may do so either by taking out a full annual subscription to *Trade and Industry*, or by subscribing to the twelve issues per year which contain *New Technology*. Readers are invited to apply for more information about subscribing to *Trade and Industry* by completing and returning the following form:

To Her Majesty's Stationery Office,
P.O. Box 569,
London SE1.

I wish to continue receiving *New Technology* as a supplement to *Trade and Industry* and would like to receive details of:

Full annual subscription ☐

Twelve issues per year subscription ☐

Name...

Address..

....

....

The Cost of Corrosion

by

T. P. Hoar and **S. Orman**

Department of Metallurgy, University of Cambridge

UK Atomic Energy Authority, Aldermaston

The Committee on Corrosion and Protection's recent report* to the Secretary of State for Trade and Industry puts the cost of metallic corrosion, and the measures taken to alleviate it, at the alarming figure of £1,365 million a year in the UK alone. This figure includes some of the losses consequential on corrosion (eg, through industrial shut-down), but does not include losses in the agricultural industries or the full costs suffered by householders in the home. According to the report, savings of no less than £310 million a year – an astonishing figure, comparable to those Budget deficits or surpluses that so properly excite public concern – could be obtained by better application of existing knowledge and methods of corrosion prevention *alone*, without any further expense on research or development. Even greater savings could be expected to ensue from new, properly oriented research.

The *Committee on Corrosion and Protection* was set up in March 1969 by the then Minister of Technology. The Committee's report – which forms the subject of this article – was presented after the change of Administration in June 1970, and hence its recommendations will be considered in the context of the Government's policy of not intervening in matters which it holds to be primarily the concern of industry itself. The views expressed in the article are those of its authors, Dr Hoar, Chairman of the Committee, and Dr Orman, Head of the Committee's Secretariat.

In conjunction with other bodies most immediately affected by the Report, the Institution of Mechanical Engineers held a two-day conference on April 20–21, 1971, at which the implications of the Committee's findings were thrown open to full public discussion. The conference, which was opened by Mr Nicholas Ridley, Parliamentary Under-Secretary of State for Industry, will be reported in a future issue of *New Technology*.

How have these colossal figures been estimated? In 1949, Dr H. H. Uhlig† attempted to put a figure on the wastage of metallic resources by corrosion in the USA, and concluded that it was some 1·25 per cent of the American gross national product. In 1956 the late Dr W. H. J. Vernon‡ undertook an estimation for the UK, arriving at a very similar conclusion: the total cost in the UK of metallic corrosion and its prevention was put at £600 million a year.

These figures have been widely quoted. They have, however, been treated with some reserve, because they were estimates made by individuals who, although greatly respected as corrosion experts, had neither the time nor the resources to make a wide-ranging and detailed survey of the whole industrial scene. Consequently, in 1969 the then Minister of Technology set up a Committee to investigate the whole field of corrosion and protection of metals in the UK. The Committee consisted of

**Report of the Committee on Corrosion and Protection;* HMSO, London, 1971.

†H. H. Uhlig, *UN Conference on Conservation of Resources,* Sectional Meeting, Lake Success (1949); *Chemical and Engineering News,* 27, 2764 (1949); *Corrosion,* 6, 29 (1950).

‡W. H. J. Vernon, 'Metallic Corrosion and Conservation', *The Conservation of Natural Resources;* Institution of Civil Engineers, London, 105-133 (1957).

14 members, drawn from industry, Government departments, research associations and universities, and was supported by a working party of three members seconded from the United Kingdom Atomic Energy Authority. The experience and interests of the Committee and working-party members were sufficiently wide to enable all aspects of corrosion and protection to be adequately considered.

The aims of the Committee were: to determine the cost of corrosion and protection in the major industries, and the savings that might be expected from improved technology; to see whether each industry employs enough corrosion experts to develop and apply improved technology; to determine what industrial education is required at all levels; to assess whether the research and development and the advisory activities in corrosion are sufficient, and, if too fragmentary, the extent to which further co-ordination is desirable and possible; and to suggest what steps might be taken to improve the dissemination of existing and new knowledge.

To obtain the necessary information as rapidly as possible, seven sub-committees, each consisting of two or three members, were formed to supplement the full-time working party and to investigate areas of interest. In a period of less than 18 months, information was obtained from more than 1650 sources. The working party and the sub-committees both relied for their information on interviews, questionnaires, letters and many personal discussions. The response from industry was extremely helpful, and approaches to organisations were generally welcomed by the managements concerned.

The cost of corrosion and protection was assessed for representative organisations covering most areas of industry and public life. From the figures given in confidence to the Committee an appropriately weighted mean was calculated, and then scaled up to give a value representative of the whole country for each group of industries. The original intention of the Committee had been to obtain information from a cross-section of companies in each industry, but it was soon found that only a limited number of firms were sufficiently corrosion-conscious to be able to estimate the cost to themselves. Other companies were unable to give any economic information, and in some cases stated that the whole problem tended to be hidden under general maintenance costs. The final estimated cost was derived from information given by organisations with a better-than-average appreciation of the effects of corrosion on their enterprises, and hence represents a *minimum* value.

The large quantity of economic information obtained by the Committee was processed by members of the Economic and Statistical Analysis Division of the then Ministry of Technology. The Committee was assisted greatly by this group, and also by the Ministry's Industrial Liaison Officers, who helped in distributing questionnaires to small firms in selected areas.

The economic findings of the Committee are summarised in the table on this page. At first sight the figures tabulated may appear to be too high to be attributable to corrosion, and it is therefore important to consider briefly the indirect expenses that add to the total cost. Some of these are:

(i) *Loss of production.* In a small plant it may sometimes be more profitable to use a cheap material, and replace it regularly, than to use a more expensive corrosion-resistant material. In a large integrated factory, however, maintenance work on one plant may cause loss of production from several others. Thus the choice of materials may be dictated by requirements beyond those of an individual unit.

(ii) *Reduction of efficiency.* The accumulation of corrosion products can reduce heat transfer in one plant, or necessitate an increase in pumping power to overcome the effects of clogging in another. Another example is the loss of critical dimensions within internal-combustion engines: it has been claimed that corrosion within these engines is more detrimental than wear.

(iii) *Product contamination.* Very small quantities of corrosion can result in discolouration or staining of a product, and the less corrosion-conscious organisations can suffer heavy losses before the cause is finally identified.

(iv) *Over-design.* The principle of over-design is the use of much thicker sections than are required for mechanical strength, to allow for the ravages of corrosion. In some circumstances it could be cheaper to use thinner sections of a corrosion-resistant material.

(v) *Maintenance of stand-by plant and equipment.* When plants have been erected containing sections or equipment susceptible to corrosion, the company may have to maintain replacement sections ready for use when corrosion failure occurs.

Estimated Cost of Corrosion and Protection in Major Industries in the UK

Industry or Agency	Estimated cost £M	Estimated saving available £M
Building and construction	250	50
Food	40	4
General engineering	110	35
Government departments and agencies	55	20
Marine	280	55
Metal refining and semi-fabrication	15	2
Oil and chemical	180	15
Power	60	25
Transport	350	100
Water Supply	25	4
Total	1365	310

Summarising, it can be said that the cost corrosion can be, and often is, very much higher than the value of the metal lost in the reaction with its environment.

A great deal (about 23 per cent: see table) of the money now consumed by corrosion could be saved if a greater degree of corrosion awareness could be introduced on a national scale. Having identified the savings which could be achieved, the industries which would benefit directly from such savings may be expected to take the necessary steps to improve their efficiency. However, a lower degree of urgency may be anticipated from those sectors of the manufacturing industries in which the savings would accrue to the user, and it is for this reason that an improvement in corrosion awareness should be made throughout all levels of industry and commerce, including 'user' organisations and individuals.

In its recommendations, the Committee points out that the provision of corrosion and protection specialists by the country's various educational establishments, and of metallurgists knowledgeable in the corrosion field, is now adequate. Furthermore, the present effort in fundamental and applied research is also deemed satisfactory, although there is room for improvement in its distribution – more work on the *prevention* of corrosion is needed. However, engineers in their qualifying courses receive little or no instruction in corrosion matters, and are consequently often at a loss to know where to find information about a corrosion problem – or indeed even to realise that the problem exists. At the higher levels of management, the non-technical executive is, in large part, dependent for his corrosion-awareness on advice from his engineers, and they too frequently are unable to give authoritative information.

In consequence, the Committee recommends the establishment of a National Corrosion and Protection Centre. Such a Centre would act as a focal point where answers to corrosion queries could be provided from the many sources of information available, and would also attempt to put inquirers in immediate contact with those most appropriate to give assistance. In cases where new research or development proved to be necessary, the Centre would either undertake the work itself or make arrangements for the work to be done elsewhere. After it had become accepted as authoritative, the Centre would aim to give assistance, whenever required, at the design stage of new projects – the stage at which probably the largest savings can be achieved.

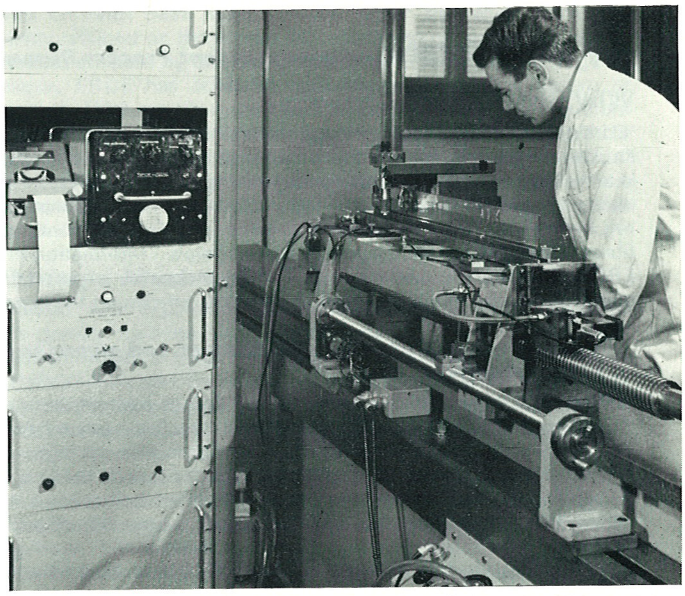
Such a Centre would have to be, and to be seen to be, completely independent and unbiased: the need for an unbiased body was emphasised to the Committee by many industrial undertakings, both large and small, and by the National Council of Corrosion Societies. It is our hope that, after full discussion, the Committee's recommendation for a National Centre will be accepted and implemented along the lines indicated above. Were such a Centre to cost even £100,000 a year, the expenditure would be only about 0·03 per cent of the £310 million a year estimated saving to the country. If industry or some other source would be prepared to provide the sum for perhaps two or three years, there are grounds for hope that thereafter the Centre would have established itself sufficiently to offer its services on a fully self-supporting basis. □

Manufacturing-Systems Technology at NEL

by P. H. Stephenson

Superintendent, Manufacturing Systems Group, and Director, Birniehill Institute, N.E.L.

Some of Birniehill Institute's modern design facilities



A lead screw calibration bench at NEL using optical gratings for precision measurement

Until fairly recently the development of sophisticated manufacturing systems in the engineering industries was restricted mainly to the large mass-producing companies, and the techniques adopted had little relevance for small batch producers. This situation is changing rapidly, however, with advances in new technologies (particularly numerically controlled machine tools and computer technology) opening up the way to new methods of production widely applicable in the engineering field. As an integrated and unified means of production, the concept of systems-engineered manufacturing technology offers considerable scope for increasing productivity and profitability. Encompassing, as it does, however, all aspects of manufacture, from product design, through production and inspection, to sales and marketing, it also raises many technical, management and economic problems which will have to be solved before the value of the approach can be appreciated and accepted by manufacturers in the UK. The rapid progress which Japan, USA and West Germany have made in developing and implementing elements of the total system – eg, computer numerical control (CNC) and direct numerical control (DNC) – constitute a threat and a challenge to the UK's relative competitiveness in the future. These considerations are reflected in the recent formation, at the National Engineering Laboratory, East Kilbride, of a new **Manufacturing Systems Group,** aimed at integrating and expanding the work on machine-tool and control technology conducted by the Birniehill Institute of Advanced Machine Tool and Control Technology and by some of NEL's research divisions.

NEL has built up an international reputation in a number of fields relevant to the manufacturing-systems concept. One example is its work on computer programs for NC machine tools. The NEL NC suite of programs cover milling, drilling, turning and (a result of collaboration with BSRA) flame cutting; of modular construction, and hence readily modifiable to suit industrial requirements, the programs have been distributed widely, on ICL computers, both in the UK and abroad. The Laboratory also offers industry a centre of expertise in the use of foreign NC computer programs compatible with its own (eg, APT from the USA and EXAPT from West Germany). Close collaboration with the Aachen Machine Tool Institute, for instance, has recently resulted in the development of a hybrid program (2CL-EXAPT 1) which, based on modules of EXAPT 1 and the NEL's NC programs, enables machining centres to be programmed for contour-milling and hole-making operations. NEL is also well-known for its development of an absolute measuring system which has been applied to NC machine tools, and exploited commercially in a co-ordinate analyser suitable for grading and checking machined plates. Other relevant NEL developments include an in-process gauging system suited to machining operations where major dimensional errors are due to tool wear and thermal distortion; optical grating tranducers for both linear and circular measurements in the machine-tool field; and an alignment device incorporating a laser beam as the reference optical path.

For its part, Birniehill Institute has concentrated in the past two years on preliminary studies of the overall manufacturing-system concept, and has identified and exposed elements of the system in a series of courses, seminars and conferences for industry. It has also undertaken some limited projects on group technology, pallet location and handling, and design of logical sequential circuits.

In the new Manufacturing Systems Group, research and development will be concentrated mainly in three closely related divisions, which will deal, respectively, with computer-aided manufacture, control systems and optical methods. **CAM Division** will continue the production of NEL's NC programs, although, in time, maintenance of the programs may become the responsibility of industry. This work will logically expand to include development of interactive programming techniques (involving use of teletype and graphic display units), particularly where they are steps towards computer-aided manufacture. New work on direct computer control of groups of NC machines (DNC), and on the associated management information systems, is also planned.

Control engineering – a vital part of CAM – will fall within the province of the new **Control Systems Division.** The present control instrumentation laboratory is to be expanded to cover also the use of advanced electronic techniques and the application of mini-computers in the control field, and the design of associated hardware.

The **Optical Methods Division,** already an acknowledged leader in the development of optical grating transducers, will continue to study, and develop the applications of, laser and holographic interferometry.

The **back-up support** required by R and D of the above nature will include an **experimental-machine shop,** which will provide facilities for NC and DNC development, in addition to experience in everyday use of NC machines. The NC equipment, which will range from simple point-to-point drilling machines to a 6-axis Molins unit, will be applied to new production techniques, such as group technology. NEL's existing **Metrology Department** will contribute its expertise to the back-up support, and Birniehill Institute's advanced design office, with its computer aids, will complete the Group's services. The metrology and experimental-machine facilities will also be employed as the basis for feasibility studies in collaboration with industry.

The Manufacturing Systems Group will work in close co-operation with the Birniehill Institute (the Director of the Institute is also Superintendent of the Group), and the Institute will act as the major interface between the Group and industry. It will also provide firms' designers, and university staff and post-graduate students (the Institute has close links with the University of Strathclyde, and several of NEL's staff are visiting professors), with facilities to work, under guidance of staff experienced in computer-aided design, with such advanced equipment as the Laboratory's Univac 1108 computer and Marconi-Elliott 905 satellite computer and graphics terminals.

The true manufacturing-system concept embraces far more than the control, planning and use of machine tools. The integration of Birniehill Institute with the National Engineering Laboratory paved the way to the setting up of NEL's new closely-knit Manufacturing Systems Group, and the concentration of effort and resources inherent in the Group's formation should facilitate development, in collaboration with industry, of hardware and software aimed at maximising the economic benefits obtainable from the use of advanced technology.

The Birniehill Institute will continue to be the Department of Trade and Industry's main centre for advanced studies and training over a wide range of mechanical-engineering design and production engineering, and to provide an avenue for dissemination of information for NEL as a whole.

More information: The Director, Birniehill Institute, East Kilbride, Glasgow. Tel: East Kilbride 20222. □

ERDE + Short Fibres + Grading + Fi

Members of the Process Research Section of the Explosives Resea and Development Establishment, Waltham Abbey, Essex, describ

New Processes for Short-Fibre Reinforcement

by H. Ziebland, *Superintendent Process Research*

Why Short Fibres?

'Continuous' fibres have obvious attractions as reinforcements for structural materials, provided that the fibres are cheap, and tensioning is an essential part of the composite-making process. These requirements are, however, not always met, and perhaps insufficient attention has been given to the advantages of using 'short' (ie, discontinuous) fibres. The case for short fibres is argued below. Information on the ERDE short-fibre processes, and on the properties of short-fibre-reinforced composites, are given in the other articles on these pages.

Discontinuous fibres may be cheaper and stronger than continuous ones

Asbestos, a plentiful and widely used fibrous mineral, not only is cheap (it costs less than fibreglass), but can, when properly handled, also be employed for the fabrication of light, rigid composites. Moreover other fibres, such as carbon fibres, can be produced more cheaply (eg, in the form of heavy tows or by using staple precursors) when intended only for 'short' applications.

Synthetic whiskers – the strongest fibres so far known – are generally available only in lengths of up to a few millimetres. ERDE has now established techniques to grade and align these minute fibres, and so make effective use of their strength.

Materials industries usually recover their scrap material. As more expensive fibres come into use, it will therefore be logical to recover them from scrap offcuts, and possibly even from disused hardware, and re-use them for short-fibre products.

Short fibres offer real advantages in fabrication

Machines for aligning short fibres can now be built capable of producing felts or preforms shaped specifically for the component to be made, and with fibre alignment controlled to meet the design stresses. Indeed different types of short fibre may even be mixed together or phased in and out through the cross-section of the materials.

Short-fibre materials also have the 'drawability' necessary for moulding into very complex shapes.

Of course, the above arguments are persuasive only if it can be shown that short fibres do reinforce effectively. Model studies have, in fact, demonstrated that absolute fibre length is unimportant, and that fibres need have only an adequate ratio of length to diameter in order to be able to carry high stresses as a reinforcement. Where the fibres can be chopped from long strands, the required length can, of course, be attained without difficulty, but asbestos, whiskers and other fibres available only in irregular lengths require a sorting process. ERDE has developed fast cleaning and grading systems to separate such fibres in relation to their end uses, and has succeeded, in some instances, in reclaiming useful fibres from relatively unpromising crude products. After sorting, both graded and chopped fibres are passed through alignment machines (alignment enables the maximum amount of fibre to be incorporated into the composite and permits optimum utilisation of fibre strength), and composites are moulded from the aligned felts so produced. A new moulding technique for rapid preparation of fibre-reinforced metals, primarily from whisker felts, has also been developed.

Fibres Used

From the range of fibres currently available, four classes were selected for use in the ERDE work: commercial 'E' glass fibre; certain varieties of asbestos; carbon fibres of high strength or high modulus; and various types of silicon-carbide whisker. Figure 1 illustrates their relative strength and stiffness properties; Figure 2 gives an indication of their size and shape. These fibres are technically important because they are light as well as strong. Carbon fibres

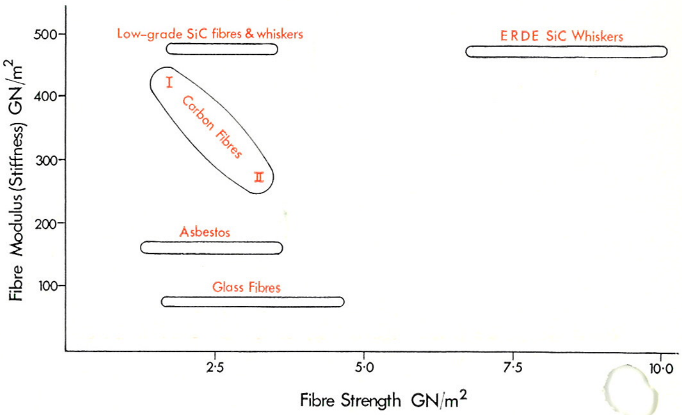


Fig. 1 Strength and stiffness of the classes of fibre used in the ERDE work

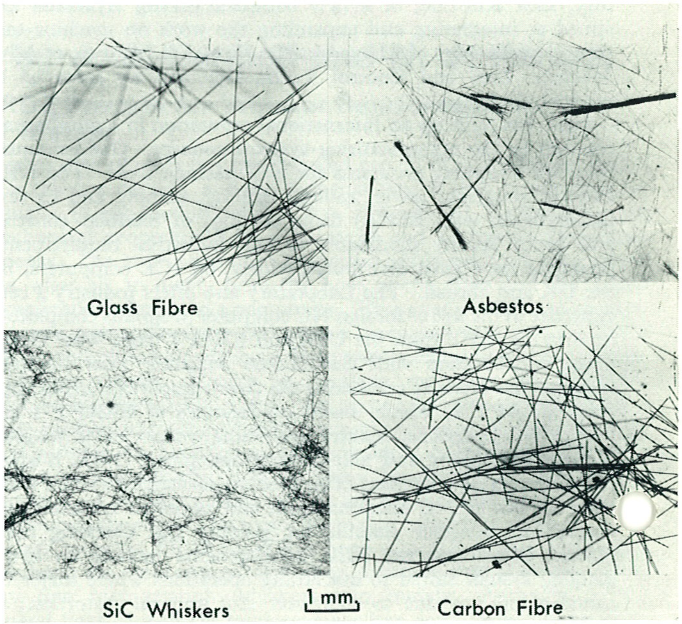


Fig. 2 Size and shape of the classes of fibre used in the ERDE work

are the lightest (density 1·6–2·0 g/cm³), followed by glass (2·4), asbestos (2·5–3·2) and silicon carbide (3·2), but in the composite these small differences in density are blurred by the weight of the resin or metal matrix.

No single fibre combines all the virtues. Glass fibre, for instance, is strong, but lacks stiffness. Its strength declines with time under sustained load, and fibreglass laminates tend to be weak after prolonged exposure to humid conditions and after fatigue cycling. Glass fibre is hence best suited to lightly loaded structures, preferably stressed in bending rather than tension (in bending, low density is more important than high modulus).

All varieties of asbestos have about the same stiffness – twice that of glass. The most common variety, chrysotile, is usually milled at the mine to a stringy mass, unsuitable for orientation. Other forms of asbestos have a more needle-like amphibole structure, and show better chemical resistance than glass and chrysotile fibres.

Carbon fibre possesses very attractive mechanical properties, and in its surface-treated form shows good adhesion to resins. Its strength still varies somewhat in production, however, and the high-modulus form could usefully be stronger.

Very strong whiskers of silicon carbide can be made, but exploitation of their full strength in reinforced materials is more difficult. They tend to be rather fine, and the majority of those available are too short for optimum performance in thermosetting resins, though

ltration Alignment + Reinforcement

rch = Improved Structural Materials

e their work on short-fibre reinforcement of metals and plastics.

they do reinforce aluminium alloys very effectively. If greater control can be achieved over their chemical preparation from low-cost ingredients, large-scale production will become feasible, putting on the market a cheap staple reinforcement of outstanding strength and stiffness.

At ERDE the likely and known health hazards associated with industrial use of fine fibres are minimised by the exclusive use of wet processing at all stages of manufacture of fibres and composite materials. □

Grading Short Fibres

b N. J. Parratt and R. W. Gooding

To use the stiffness and strength of short fibres to maximum advantage in a composite material, the ratio of fibre length to diameter must be above a certain value. This value depends on the stress to be carried in the fibre, the shear modulus of the matrix and the interfacial shear strength between fibre and matrix. Values of aspect ratio (ie, the length/diameter ratio) required for thermosetting-resin matrices range from 300/1 or more for high-strength fibres, to 30/1 for certain coarse fibres of asbestos (which are, in effect, bundles of very fine fibrils). Aspect ratios as low as 20/1 permit the fibres to carry high stresses in certain reinforced metals, and fibre bundles of this shape are also used to reinforce thermoplastics which must flow smoothly during moulding. Thus to achieve optimum, reproducible properties in composites, control of length and diameter is essential. The clean, economic wet processes developed for this purpose are outlined below.

Control of Diameter

Dispersed particles and fibres denser than water may be separated, on the basis of diameter, via their surface-drag/mass ratio: this is the principle of such devices as the elutriation column, the centrifuge and the hydrocyclone. The hydrocyclone, which is already widely used for mineral extraction, cleaning of wood pulp and removal of 'shot' from glass wool, is very effective for continuous separation of fi[illegible] It can be regarded as a kind of continuous centrifuge in which only the working fluid is rotated. An aqueous dispersion, injected tangentially into the base of a conical container, forms a vortex; the main flow is then removed from the basal centre of the cone; and a small flow is drawn off from the apex of the cone, so removing the coarser or heavier elements which become concentrated there. The particle diameter at which separation occurs is governed by input flow rate and cyclone diameter.

Perfect separation cannot be achieved with a single hydrocyclone, but cascade circuits can be designed to give adequate performance at a single pass, and cleaning and separation units of this type can be inserted in a continuous feed of dispersed material.

Separation by Length

Fibre length distributions are commonly analysed by passing dilute suspensions of the fibres through a series of screens or sieves of different mesh size, and then collecting and weighing the separated fibres. Some excellent classifiers of this type are on the market, but their output is often too small to permit even experimental work on the collected products. Bar and screen separators are used industrially, but generally for recovery of solids in bulk, or for filtration of liquids, not for accurate length grading.

Experiments have shown that fibres can be separated, on the basis of length, only when a single layer of fibres is screened, since any layer of fibres retained by the screen will trap shorter fibres. In the case of very fine fibres such as whiskers, a single layer might be less than 1 micron thick, and hence very large screen areas would be needed to obtain even a minimally useful output. This drawback has led to the development of rotating screen machines from which the product can be continuously removed. A number of laboratory machines operating on this rotary principle have been built and sold.

Gravity Machines

In operating a rotating screen machine, a dispersion is fed into a screening wheel, and the water and short fibres fall through the screen under gravity, while the longer fibres retained by the screen are sprayed off with fresh water. Some water and short fibres are inevitably retained on the screen, but sharpness of separation can be made more efficient by double screening, with feedback. Using this technique, ERDE has achieved separations down to a length of 30 microns. With gravity machines, however, output of retained fibre is only modest in relation to screen surface area (about 0·5 kg/m²hr for asbestos, and only 0·015–0·15 kg/m²hr for whiskers), and, if speed of rotation is increased even moderately, insufficient time is left for drainage under gravity, and fibre removal by spraying also becomes ineffective.

Centrifugal Machines

Calculation and experiment had shown that at high rotational speeds gravity drainage could be replaced by centrifugal drainage, completed within a single revolution. With centrifugal drainage the retained fibre can be blown off continuously with an air blast, and recovered as a concentrated slurry – for example, asbestos is recoverable at an output rate of 40 kg/m² hour. In the present ERDE pilot plant the screening stage is totally enclosed and the blown air is recycled back through the fan. Length separation is superior to that of gravity machines, and the cost of grading is expected to be small. At present pilot-plant output of retained asbestos fibre is about 25 kg/hour, but potentially could be increased by an order of magnitude with further increases in rotational speed and screen area. □

Short-Fibre Alignment

by G. E. G. Bagg and L. E. Dingle

If the properties of fibre and whisker reinforcements are to be used to maximum effect, the maximum possible amount of reinforcement has to be packed into the composite (without, of course, damaging the fibres in the process). High packing fractions, however, can be achieved only by a substantially parallel alignment of fibres, since misalignment of a relatively small proportion is sufficient to cause a disproportionately large decrease in fibre-packing density. The task is not made any easier by the fact that fibres can easily be damaged (so reducing their aspect ratio, and hence adversely affecting the properties of the composite) by forces acting on them during alignment, or by use of high pressures in the fabrication stage to produce a high packing fraction from poorly aligned fibres. The stringent alignment requirements, coupled with the fact that many high-strength whiskers and fibres are too short to be spun into line, rule out the use of conventional textile and paper-making alignment processes. All these difficulties have been overcome by the development of techniques which enable short fibres (generally 0·01–10 mm long) to be processed into a dense highly-aligned fibre mat, with little fibre damage from a random fibre or whisker wool. The operation can be broken down into three separate unit sequences:

Dispersion of the fibres in a liquid carrier medium, to a dilution ensuring little or no interaction between them during the alignment process, the suspension being sufficiently stable to prevent flocculation or separation of fibres in the plant.

Alignment of the fibres by continuous acceleration of the carrier medium in which they are suspended. The resulting progressive change in velocity aligns the fibres in the direction of the fluid motion, and the aligned fibre suspension may then be ejected, in the form of a jet or sheet, through an orifice or slit.

Removal of the carrier fluid without disturbing the fibre alignment, either by a rapid filtration process or by rapid solidification of the extruded thread or sheet followed by removal of the carrier by some suitable physical or chemical process.

The Alignment Process

The initial aim was a mechanised process producing a uniform, highly orientated fibre mat acceptable to industry for exploitation on a

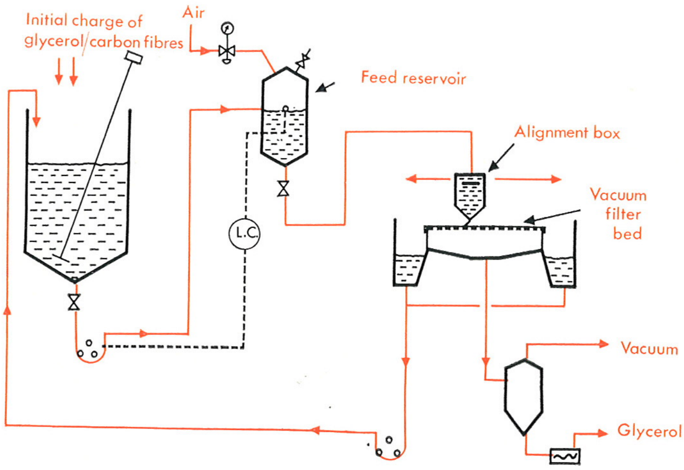


Fig. 3 Flow diagram of ERDE filtration alignment process

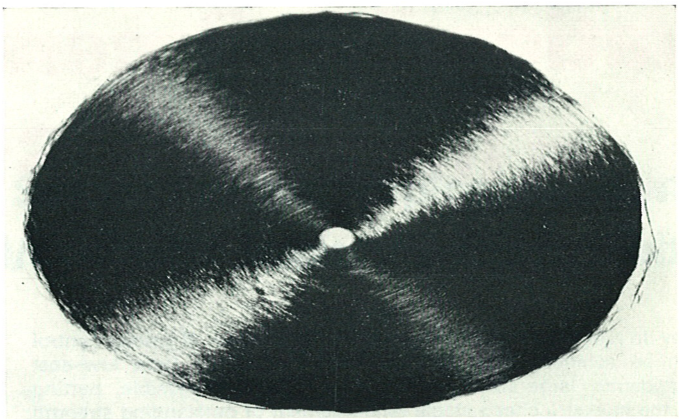


Fig. 4 Circumferentially aligned short staple carbon-fibre felt

large scale at a low processing cost. As at present operated, the ERDE filtration process uses a dilute suspension of fibres in glycerine, the concentration depending on fibre properties. As shown in Figure 3, a peristaltic pump, actuated by a level controller, pumps a homogeneous suspension of discrete fibres from the mix tank to the feed reservoir, which is pressurised by a compressed-air supply. Thence the viscous dispersion flows to the alignment box, where it is extruded through a profiled slit at constant throughput. The alignment box traverses over a vacuum filter bed, in a horizontal plane and at right angles to the slit length, the rate of travel being somewhat greater than the rate of extrusion of the dispersion, so ensuring that the film of aligned fibre is deposited, through the slit, on to the filter surface without disorientation. A rest period at each end of the filter bed allows the carrier medium to be sucked away from the fibres. Any unused extruded dispersion collects in troughs at each end of the filter bed, whence it is recirculated to the mixing tank by another peristaltic pump. Using a high-throughput vacuum pump and a low-resistance filter surface, the glycerine in the aligned fibre mat on the filter bed is removed, rapidly and virtually completely, between passes, and is recovered and recycled to the dispersion stage. By repeated layering, the aligned sheet of fibres can be built up to give an ultimate composite thickness ranging from 0·025 to 1·5 mm, and any carrier still remaining is removed by gentle water-spray washing. Concentration of the resultant aqueous glycerine enables the glycerine cycle to be made a completely closed one.

Scope of the Process

Both batch and continuous filtration-alignment plants have been employed successfully to align graded asbestos, graded whiskers of silicon carbide and silicon nitride, chopped carbon fibre (high-modulus and high-strength), chopped glass fibre, and homogeneous mixtures of different fibres. Fillers or other powdered material can be incorporated at the alignment stage, and the continuous plant could easily be extended to include a resin-impregnation sequence, the product then becoming a continuous length of aligned 'prepreg' material. Glycerine has been found to be suitable as carrier fluid, since it has a viscosity which facilitates the handling of the suspension; many other liquids may also be used, however, and in certain instances it might be desirable even to use a solution of the matrix resin itself. The fibre mats produced by the process exhibit a high degree of alignment (typically, over 90 per cent of all fibres lie within a few degrees of the preferred direction), and the small percentage of transverse fibres also present impart good handling characteristics to the material. Asbestos and whisker mats may be handled dry – a feature which, particularly in the case of whisker mats, greatly facilitates metal-matrix infiltration. Carbon-fibre felts are, however, very fragile, and need a binder, such as a few per cent polymethylmethacrylate or resin.

The alignment box is designed to give an aligned sheet of uniform thickness and quality. Any variations in fibre quality within a batch are evened out by preparing the suspension from a homogeneous mixture of chopped or graded fibres, and the mats are therefore built up from a random assortment of aligned short fibres. The resulting felts exhibit very good consistency and property reproducibility, a characteristic which is essential for engineering applications. Since the axial mechanical properties of composites are sensitive to the degree of alignment, close control of the alignment process is essential, and methods of measuring alignment by non-destructive techniques are therefore being developed.

The versatility of the filtration process can best be demonstrated in relation to the scope it offers for aligning the fibres how and where required. An individual ply layer can be as thin as a fibre diameter, and it is therefore but a short step to the production of composite felts of mixed fibres in which expensive, stiff fibres are placed only in critically stressed areas, or as a very thin skin for sandwich-type construction. By laying down successive layers of fibre at 60-degree angles, so-called planar, pseudo-isotropic material can be produced as a felt to any thickness and in a balanced condition. There has been demand also for mats with more complicated orientations, such as with circumferential or radial alignment: an example of such a product is shown in Figure 4. ☐

Reinforced Metals and Alloys

by J. C. Cannell and N. J. Parratt

ERDE Process for Whisker Reinforcement of Metals

A great deal of work has been carried out on fibre-reinforced metals over the last decade, and the fact that few, if any, composites are actually in production reflects the difficulty of combining good mechanical properties with a practical and economic fabrication process. The improvement in properties achieved by reinforcement has, after all, to justify both the cost of the fibre and the added complication of making a composite. Fibre cost is related to production and availability, and will not be discussed further here. What will be considered is a recently developed method of moulding fibre-reinforced metals. Similar to pressure moulding of reinforced plastics, but somewhat faster, the technique was derived from a study carried out using a plastics press and conventional steel tooling. It is suitable for production of completely or partially reinforced small cast components, and for batch production of intermediate shapes, such as billets, bars, casting inserts, etc, and the prospect of continuous sheet manufacture is now also being investigated.

Until recently, ERDE work has been directed almost exclusively to solving the most critical fabrication problem, that of incorporating very fine high-strengh whiskers into metals. Research in the general field of whisker reinforcement has centred mainly on reinforcement of aluminium alloys, in an attempt to improve on light-weight-alloy composites reinforced with boron fibre and carbon fibre, and the established alloys of titanium, aluminium and beryllium. Both boron- and carbon-reinforced composites show poor tensile strengths transverse to the fibre direction, so that in actual design they tend to be heavier and little better than their resin-based counterparts, apart from the fact that they retain the metallic attributes of good thermal and electrical conductivity, good oxidation-resistance and high melting point.

The results of early work on whisker reinforcement of metals were not very encouraging. Low strength and porosity are reported in the literature, despite the application of such elaborate techniques as metallising the fibres prior to infiltration or solid-state diffusion. In studies involving use of conventional pressure die casting for infiltrating somewhat coarser fibres, penetration was found to be uneven, and porosity still common. ERDE has now, however, achieved a significant step forward in whisker reinforcement with the following simple technique: felts of aligned whiskers are placed in an open mould and the matrix metal is poured in; the mould is closed and a controlled pressure cycle is applied; after a few seconds to allow for complete solidification the product is removed.

Whiskers of silicon carbide are stable in molten aluminium, and such composites can be produced without problems by the technique. Since, moreover, the contact time between molten metal and fibre can be reduced to less than one second, the process may permit even the use of nominally incompatible combinations (eg, silicon nitride with aluminium, magnesium or copper). Penetration is thorough, and whiskers with a diameter as small as 0·1 micron have been incorporated successfully as reinforcements.

TABLE 1 Comparison of the longitudinal tensile strengths of composites of cast HD 543 alloy reinforced with various SiC-whisker felts

Type of whisker felt	Submicron† retained 100 mesh	Micron* retained 100	Micron* retained 400
Vol % whiskers	22	21	20
Tensile Strength			
tonf/in^2	48 (48)	60	37 (48)
10^3 lbf/in^2	107 (107)	135	83 (107)
GN/m^2	0·74 (0·74)	0·93	0·57 (0·74)

*Whisker diameters : 0·5 – 2 × 10^{-3} mm
†Whisker diameters : 0·1 – 1 × 10^{-3} mm

TABLE 2 Effect of whisker volume loading on longitudinal tensile strength of cast HD 543 alloy

Vol % whiskers*	Tensile strength (GN/m^2)
0	0·25
15	0·66 (0·79)
21	0·93
27	0·97

*Retained 100 mesh micron-size SiC whisker

TABLE 3 Off-axis tensile strength of cast composites of HD 543 alloy (strength of cast unreinforced alloy: 0·25 GNm^{-2})

Whisker material	Vol %	Tensile strength (GNm^{-2})			
		0°	20°	45°	90°
Submicron (retained 100 mesh)	22	0·74 (0·74)	0·63 (0·76)	0·40 (0·57)	0·40 (0·43)
Micron (retained 100 mesh)	21	0·93	0·51 (0·63)	0·45	0·38
Micron (retained 400 mesh)	24	0·62	0·66	0·49	0·35 (0·46)
Random submicron (retained 400 mesh)	18	0·41 (0·45)	0·41 (0·45)	0·41 (0·45)	0·41 (0·45)

Properties of Moulded Whisker Composites

The data tabulated on this page are only illustrative: as work progresses, mechanical properties are being continually improved. The tensile tests were made on small Hounsfield specimens machined from 7-mm-diameter cylinders. The contribution of the cast matrix to composite strength is small, but strength can be increased by a stabilising treatment at 190°C, as the figures in brackets in Tables 1–3 show.

The degree of fibre alignment in the felt varies a little with the type of whisker used, but generally gives substantial off-axis and transverse properties in the cast material (see Table 3): at a rough estimate, the effective reinforcing strength of the whiskers is about 5 GN/m^2. At 21 per cent whisker reinforcement, Young's modulus in the nominal direction of alignment is twice that of the unreinforced aluminium alloy, and in the transverse direction about 50 per cent greater than without reinforcement. Improvement in fatigue properties is roughly pro-rata with the increase in modulus. Strength, creep and fatigue properties at elevated temperatures are currently being evaluated, and first results are very encouraging.

The composites which are strong in tension are also very strong in flexure and compression, and values exceeding 1·4 GN/m^2 for both these properties have been measured in the direction of fibre alignment. Fracture energy is only moderate (about 0·5 J/cm^2 of each crack face), but it increases with tensile strength, as the fracture mechanism begins to involve a tearing of the original felt laminate. The composites exhibit negligible ductility at room temperature, but can be formed at high temperature; indeed research on well-aligned model composites has suggested that deformations of up to 50 per cent are possible, and may even lead to improved properties. Alignment of whiskers by subjecting randomly-reinforced billets to hot extrusion, with deformations exceeding 1000 per cent, led to severe breakup of long whiskers, and this technique is thought to be more suitable for use in aligning low-grade fibres, with the aim of gaining stiffness rather than strength. Table 4 lists data on some properties of the extruded material.

All the property data tabulated here were obtained from cast composites incorporating whiskers grown and processed at ERDE. Weaker whiskers can be incorporated in volume loadings of up to at least 40 per cent by the present process, so that preparation of composites which are even stronger and stiffer depends largely on the achievement of more precise orientation and closer control of whisker diameter. The ERDE moulding technique is suitable also for application to more commonplace fibrous materials (eg, asbestos, glass and fine steel wires), as a means of improving the properties of metal components in the broader sense – ie, without particular regard to their specific weight as such. ☐

TABLE 4 Properties of RR58 alloy reinforced with 18 per cent SiC whiskers (whiskers aligned by extrusion from random billets, final L/d 7). All specimens fully heat-treated, quenched and aged.

Material direction	Young's modulus		Compressive strength		Tensile strength		Fatigue strength at 10^7 cycles (plain specimens in rotation bending)	
	10^6 lbf/in^2	GNm^{-2}	10^3 lbf/in^2	MNm^{-2}	10^3 lbf/in^2	MNm^{-2}	10^3 lbf/in^2	MNm^{-2}
Wrought RR58	10·4	71	71	490	62	430	23	160
Extrusion axis (reinforced RR58)	17·5	120	112	770	79/83	540/570	31/36	210/250
Transverse axis (reinforced RR58)	12	83	—	—	45/56	310/390	—	—

Short Fibres in Plastics

by H. Edwards and L. E. Dingle

To make full use of the benefits – particularly the weight savings – offered by advanced reinforced plastic composites, and to increase their range of application, they need to be made suitable for use in complicated structures (eg, fittings, housings and complex mechanical parts) as well as in the geometrically simpler forms for which continuous filament is now employed. Short-fibre-reinforced composites can provide just this versatility.

Although useful composites have been produced by incorporating random distributions of glass or asbestos short fibres in plastics matrices, very little increase in modulus and strength is achieved when the same techniques are applied to the more recently developed very stiff and very strong fibres, such as whiskers and carbon fibres. This outcome is due mainly to excessive breakdown of the fibres during consolidation by the conventional processes, with the result that only a small fraction of the fibre properties are realised in the final composite. As described elsewhere on these pages, fibre alignment allows the fabrication of components containing a high volume packing fraction of fibres at sufficiently low moulding pressures to minimise fibre breakdown, and alignment is therefore an essential prerequisite to using the high strength and modulus of the new fibres to maximum advantage.

The ERDE filtration process, which produces highly aligned resin-impregnated short-fibre sheet material ('prepreg') possessing excellent handling properties, is arousing considerable interest amongst industrial users. The aligned sheets are keyed together by the small proportion of misaligned fibres which are always present and these cross fibres provide the 'green' strength required for cutting and draping the mats. In combination with the ability of the short fibres to 'slip', this green strength enables the prepreg to be formed to the profile of a mould without destroying the uniformity of the fibre distribution and orientation. It is hence feasible, by matched-die compression moulding, to produce complicated three-dimensional shapes, with complex curvatures, for such articles as housings, cones, flanged or ribbed tubes, rotating parts, etc. By controlling the resin viscosity by B-staging the prepreg, or by adding fillers, it is possible to vary the flow conditions in the mould – from resin flow only, with complete retention of fibre orientation, to both resin and fibre flow, which is often necessary, for example, for production of ribbed components.

Any resin suitable for 'pre-pregging' can be used with the aligned short-fibre felts, and, for instance, composites have been successfully made with polyester, epoxy, phenolformaldehyde and polyimide resins. The axial flexural properties of the composite appear to be almost independent of the resin system used, but application of the correct composite cure cycle is crucial to attainment of articles of consistent quality. The consolidation pressure must be applied slowly as the prepreg is gradually heated up in the mould, and full pressure at a point just before gelation of the resin. The moulding pressure necessary to achieve the desired packing fraction depends on the degree of alignment and the geometry of the fibres, and, in general, prepregs made from short fibres require higher pressures than those incorporating an equivalent volume loading of continuous fibres. Hence a very high degree of alignment is required if large mouldings are to be produced from aligned short-fibre prepreg at conventional autoclave pressures (up to 7 bar).

Figure 5 typifies the axial flexural properties exhibited by composites made from standard prepregs incorporating different types of short fibre. As can be seen, about 70 per cent of the fibre strength and 90 per cent of the fibre modulus are realised in the alignment direction. Reasons for non-realisation of full fibre properties include imperfect alignment, and inefficient stress transfer between fibres due to poor adhesion or uneven fibre distribution. The loss due to misalignment should be compensated by the concomitant increase in off-axis properties, and the stress-transfer problem would be alleviated by extending the scope of the process to incorporate longer fibres. Transverse flexural properties depend on the degree of fibre alignment, decreasing as the alignment improves, and approaching ultimately those of aligned continuous-fibre composites. Other composite properties, such as tensile, fatigue and creep characteristics, are being determined.

In Figure 5 the properties of composites are related to a uniform fibre-volume packing fraction of 0·5. The optimum values obtained at higher fibre loadings are given in Figure 6. In general, reinforcement efficiency (ie, the percentage of fibre strength utilised) tends to fall with increase in fibre volume loading, although the absolute values of strength and modulus continue to rise – an effect which is more noticeable with high-modulus fibres, because the large moulding pressures necessary to produce high packing fractions tend to cause excessive fibre breakdown. However, high loadings of glass fibre and graded anthophyllite asbestos (up to 70 per cent fibre by volume) can be obtained, and ultimate flexural strength and modulus considerably increased, by using high-integrity bundles. Although such tightly bound aligned bundles may have an overall aspect ratio as low as 40/1, good reinforcement efficiency can be achieved provided that they are slightly dispersed in the glycerol suspension before alignment. This approach enables composites to be moulded at much lower pressures than those applicable to a completely dispersed material. The high mechanical properties achieved at ERDE with composites reinforced with graded anthophyllite are particularly significant, since anthophyllite has high chemical resistance. It can therefore be used to replace crocidolite, which is currently used in chemical plant, but is becoming increasingly difficult to obtain in this country as a result of restrictions imposed on it by recent asbestos-handling regulations.

Figure 6 demonstrates the enormous potential of silicon-carbide whiskers grown at ERDE. Assuming the average reinforcement efficiency of short fibres to be 70 per cent at a volume packing fraction of 0·5, production of silicon-carbide-reinforced plastic composites with a strength of 3·5 GN/m² (500,000 lbf/in²) is conceivable. Such strength has not been attained to date simply because the whiskers are so fine (the average diameter is less than 1 micron), and to achieve an alignment good enough for incorporation of high volume packing fractions without fibre breakdown is difficult. Further progress must await the availability of thicker, longer fibres.

Short-fibre reinforcement will find widespread application only if the economic factors are right, and processing costs have therefore also to be kept to a minimum. Already at ERDE unidirectional short-fibre prepregs are being prepared by a mechanical continuous process, and, with slight modification, this process could be adapted to produce planar, pseudo-isotropic or cross-plied prepreg (in which successive layers of fibres are deposited at a 60- or 90-degree angle to the preceding layer), so facilitating production of composites with no tendency to warp on moulding. These modifications of unidirectional deposition, coupled with the feasibility of making prepregs with radial or circumferential alignment, and the possibility of programming to produce complex two- or three-dimensional alignment patterns matching the predicted stress distributions, open up a wide field of application. For example, the principal stresses in rotating discs consist of radial and circumferential components which vary with distance from the centre. Work is in progress to apply short-fibre reinforcement also to this type of composite.

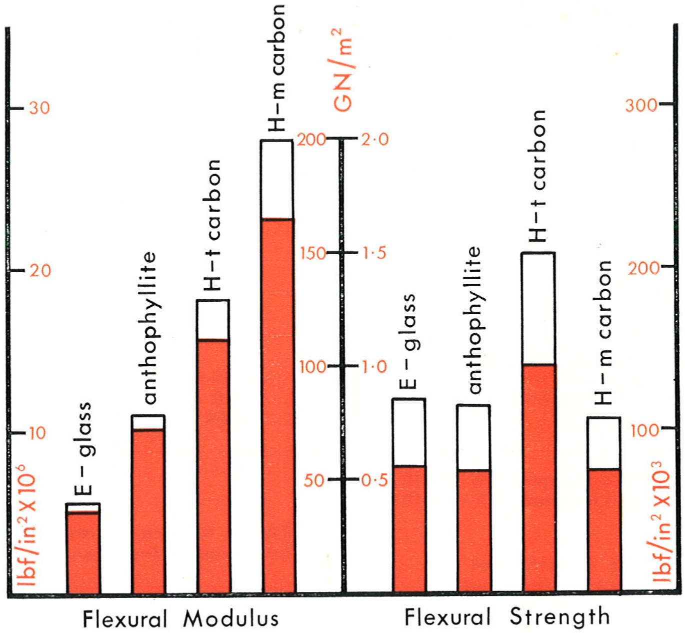


Fig. 5 Axial flexural strength and modulus values for short-fibre-reinforced composites. Volume packing fraction 0·5; epoxy-resin matrix. Actual property data in red; theoretical maximum (calculated from fibre-property measurements) in white

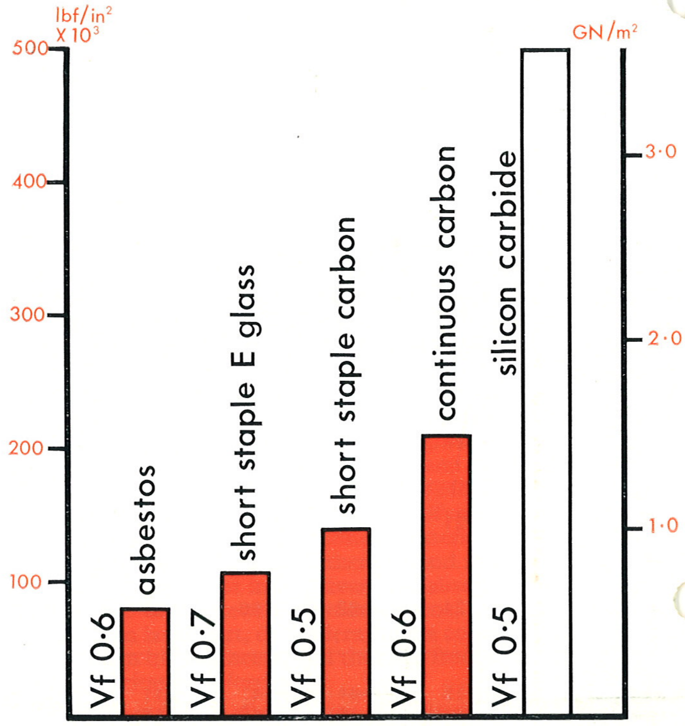


Fig. 6 Comparison of flexural-strength data for various reinforced plastics at optimum packing fraction (Vf). SiC column indicates potential strength only

New Technology is prepared by the Department of Trade and Industry. It is obtainable free of charge on application to the Central Office of Information, Hercules Road, Westminster Bridge Road, London SE1.

More information: Where possible, items in *New Technology* indicate the best sources of further information. Readers are advised to seek information on matters relating to *New Technology* also from the following DTI regional offices: Edinburgh 031-225 1822; Cardiff 62131; Newcastle upon Tyne 27575; Manchester 061-832 9111; Leeds 38232; Nottingham 46121; Birmingham 021-644 8191; Bristol 21071; South East and East Anglia 01-799 5688. In Northern Ireland, information is given by the Dept. of Industrial and Forensic Science, Belfast 21722.

Editorial office: Department of Trade and Industry, Room 439, 1 Victoria Street, London SW1. Tel: 222 7877, ext. 2620.

Printed in England for Her Majesty's Stationery Office at The Baynard Press London EC1