Design and Engineering of Carbon Brakes

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Phil. Trans. R. Soc. Lond. A 1980 **294**, 583-590
doi: 10.1098/rsta.1980.0068

Phil. Trans. R. Soc. Lond. A **294**, 583–590 (1980)
Printed in Great Britain

Design and engineering of carbon brakes

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[Plate 1]

The need for weight saving on Concorde stimulated the development of lightweight aircraft brakes. Carbon has long been recognized as a major constituent of brake friction materials and a carbon carbon composite has been engineered to provide adequate structural, thermal and friction characteristics for these disks. The use of carbon brake disks offered a 60 % weight saving compared with steel.

Design of the composite is particular to the application. Orientation of the fibres on account of stress and heat flow requirements is vital to the achievement of a successful design. The material is considerably anisotropic and represents a compromise between strength and thermal properties, and manufacturing costs. Dunlop selected the chemical vapour deposition of carbon into a carbon fibre lay-up as the method of manufacture of the composite for Concorde brakes. The introduction of an incompletely developed process and a new composite brought novel problems to both design and manufacturing staff. Material property evaluation and extensive quality control practice played a major role.

INTRODUCTION

A composite material consisting of two different forms of carbon scarcely seems to be a likely candidate for a vital piece of aircraft mechanism, particularly one that is subjected to high mechanical loads, high thermal shock and is designed as a replaceable wearing part. It is therefore understandable that years of research and development went into the design and manufacture of the composite now adopted for certain aircraft brakes.

The design of this carbon fibre reinforced carbon composite, which is generally known as a carbon carbon composite, has had to be a compromise between a number of criteria some of which are seldom considered in other composite material designs. The objectives are not completely fulfilled but there are opportunities for further developments.

The first carbon carbon composite aircraft wheel brakes to go into regular airline use were those provided by Dunlop in 1973 for initial trial on a VC10 aircraft followed a year later by standard fitment on Concorde.

GENERAL BACKGROUND

Aircraft brakes are usually multiple disk brakes, rotors sandwiched between stators, the rotors driven by the wheel and the stators held stationary by the brake structure. The rotors and stators are generally steel disks faced with sintered metal friction and wear surfaces. Braking action is achieved by pressing the disks together with the use of hydraulic power. A section of the Concorde wheel and carbon brake is shown in figure 1.

The aircraft brakes are required to provide the frictional torque that stops the aircraft and to absorb the heat generated from conversion of the aircraft's kinetic energy, 272×10^6 J in the

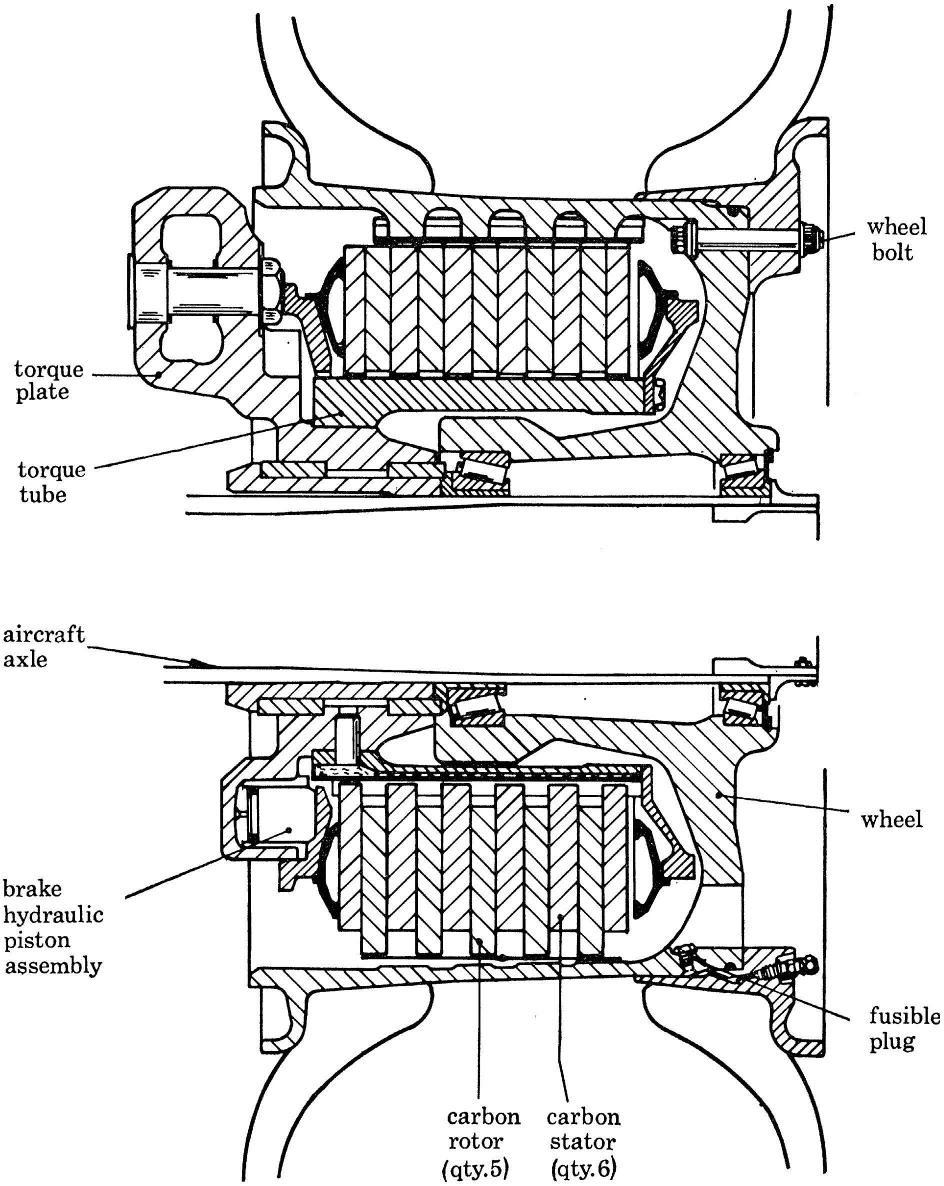

FIGURE 1. Concorde wheel and carbon brake.

case of Concorde during its maximum normal landing. The heat is generated in 20–30 s and the proportion of heat rejected to the atmosphere in this period is negligible; the disks act therefore as a heat sink.

All aircraft constructors and operators are anxious to reduce the aircraft structural weight as far as they can within economic limits and the performances of vertical takeoff, high performance and supersonic aircraft are particularly sensitive to weight. Carbon, of density 2.26 g/cm^3 and of specific heat nearly $2\frac{1}{2}$ times that of steel, intrinsically offers a 60 % weight saving for a similar brake temperature operating range. A carbon carbon composite offered the possibility of achieving physical properties that would allow the brake to be structurally adequate and have good friction and wear characteristics. For the Concorde the opportunity of saving over 600 kg on the aircraft structural weight was of major significance.

Loading conditions of a composite disk

The properties one seeks in a brake disk material are:

(i) high thermal capacity;
(ii) good strength, impact resistance and strain to failure;
(iii) adequate and consistent friction characteristics;
(iv) high thermal conductivity.

Of these requirements the thermal capacity and strength are fundamental, whereas if the friction requirements are not inherent in the material, means can usually be found of adding this property. The high thermal conductivity is necessary to avoid obvious problems arising from high energy input rates, thermal expansion and property degradation at elevated temperatures. A comparison of some of the properties of the traditional brake disk materials, copper and steel, with those of carbon carbon composite are given in table 1. The properties quoted for the composite must be regarded as sample figures since they can be changed significantly by heat treatment and since the material is considerably anisotropic, being dependent upon the type and manner of lay-up of the fibre and the general dimensions of the part.

Table 1. Some properties of brake disk materials

	carbon carbon composite	steel	copper
specific heat/($J\ g^{-1}\ K^{-1}$)	1.42	0.59	0.42
tensile strength/MPa	66	410	240
impact resistance/J	0.7	110	55
percentage strain to failure	0.55	33	40
thermal conductivity/($J\ m^{-1}\ s^{-1}\ K^{-1}$)	10–150	59	346
$10^6 \times$ coefficient of linear expansion/K^{-1}	0–8	14	18

The properties of a high strength graphite are compared with those of a carbon carbon composite in table 2, which illustrates the advantages in strength and conductivity that the composite offers.

Table 2. Properties of a high strength graphite compared with a carbon carbon composite

	high strength graphite	carbon carbon composite
density/($g\ cm^{-3}$)	1.82	1.6
flexural strength/MPa	55	100
compressive strength/MPa	125	300
thermal conductivity/($J\ m^{-1}\ s^{-1}\ K^{-1}$)	85	30 (perpendicular) 100 (parallel)

For a maximum normal landing carbon carbon composite brake temperatures of 500 °C are typical; for an emergency abandoned take-off, temperatures up to 1300 °C can be experienced. These temperatures are soak temperatures in the heat sink a few moments after the end of the heat input. Higher brake temperatures could be employed if it were not for the limitations applied by the surrounding metal structural members.

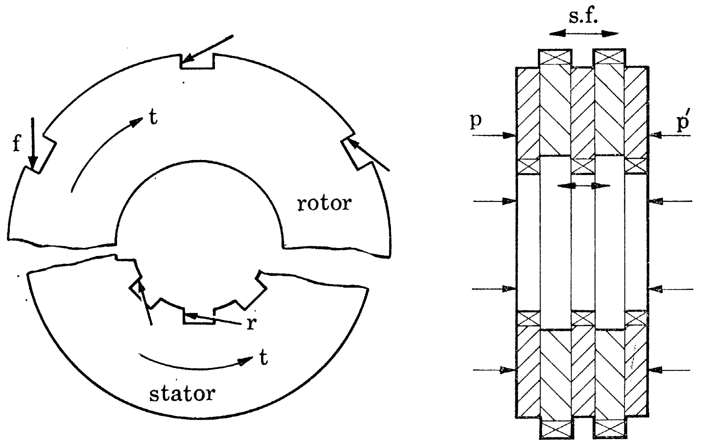

Figure 2. Forces on brake disks. f, wheel drive force; t, friction torque; r, reaction; p, p′, clamping pressure; s.f., spline friction.

The forces on a brake disk are indicated in figure 2. Frictional forces on the faces of the disks are reacted at the drive slots. The sharing of the loads between the drive slots is dependent upon the accuracy of machining and particularly upon the deflexion of the mating components.

The wheel is used as one of the drive components and when a ground load is applied it deflects in the general form shown for a 14 in (35.6 cm) diameter wheel in figure 3. The Concorde wheel, of 22 in (55.9 cm) diameter, when subjected to a critical loading case of combined radial and side limit loads has a radial deflexion at the 6 o'clock position of nearly 1.3 cm.

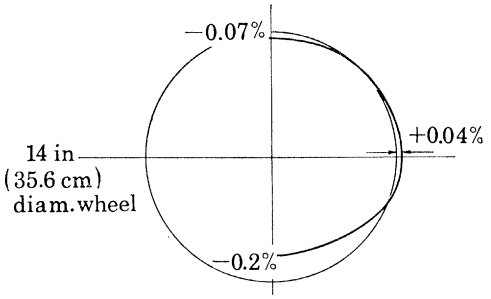

Figure 3. Wheel deflexion under vertical loading. Radial deflexion, mag. × 66.67.

The wheel and rotor drive tenons and slots are designed to accommodate the wheel deflexion but it is inevitable that the torque is taken on relatively few drive points at any instant and that loading is cyclic. Thermal movements of the disk are relatively small.

The thermal loading of a disk is extremely severe and has a controlling influence on the brake design. Brake frictional contact is a thermo-elastic and wear phenomenon. Figure 4 illustrates the sequence of events. Initially, adjacent disks contact one another at local points only and the work done at these points causes local expansion. Owing to rotation of one of the disks a narrow annular band of contact results. Further work and expansion takes place at the radius until heat flow, wear at the band of contact, and changes of mechanical loading from adjacent disks cause a new band of contact to become established. The work at the first band diminishes, the material cools locally, and because wear has taken place that particular band of contact is unlikely to be re-established for some while.

This mechanism is reported in publications by Barber (1969) and Kennedy & Ling (1973) and has been demonstrated to take place on carbon carbon composite brakes. The rate of work per band of contact means that transient temperatures at the contact surface are well in excess of 2000 °C.

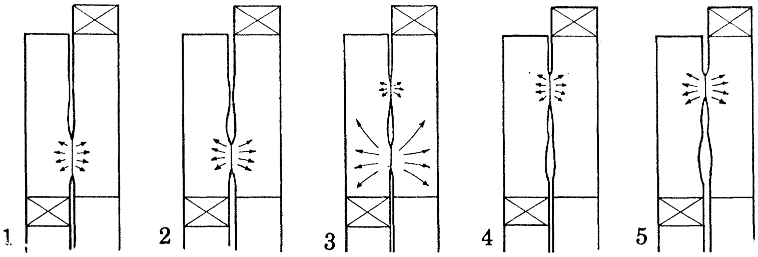

Figure 4. Thermo-elastic and wear effect causing bands of contact.

The importance of adequate distribution of mechanical clamping loads and design of the brake structure to achieve this is discussed by Stimson & Dowell (1973).

Design of a carbon carbon composite disk

Fibre orientation in a disk is determined by heat flow requirements as well as structural ones, and there are four criteria for preferred fibre orientation as shown in figure 5.

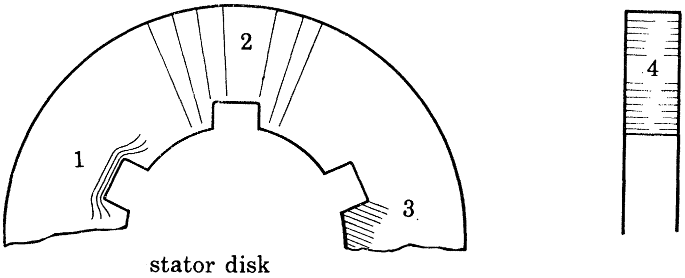

Figure 5. Preferred fibre directions; 1, flow around notches (strength); 2, radially at surface (heat flow); 3, 45° to shear at slot (strength); 4, normal to disk surface (heat flow).

These criteria are:

(i) to minimize the effect of the drive slot;
(ii) to conduct heat radially;
(iii) to withstand shear forces at the drive slot;
(iv) to take heat into the body of the disk;

Two engineering solutions suggest themselves:

(*a*) woven cloth of carbon fibre lying in the plane of the disk with layers rotated relative to one another to achieve near isotropy in the plane;
(*b*) needled random mat, moulded to shape.

The advantages of the cloth lay-up process are that it provides a good product and is readily achievable. On the other hand, it is wasteful of carbon cloth and is time consuming, both of which lead to an expensive product.

The mat or chopped tow alternative is one that has advantage of lower cost but brings with it greater difficulty of manufacture and perhaps greater variation in properties within each disk and within a batch of disks.

Manufacture of carbon carbon composite disk

It is helpful to appreciate the nature and method of manufacture of carbon carbon composite material. There are two routes by which manufacture takes place; one involves charring of a resin, the other, which is the one preferred by Dunlop, involves gaseous deposition of carbon.

Essentially the process is one of taking fibrous carbon, not necessarily high modulus or high strength carbon fibre used in carbon resin composites, bonding the fibres with carbon deposited by cracking an organic gas, such as methane, at a suitable pressure and temperature.

Concorde brake disks are manufactured by carbonizing rayon cloth, cutting the resulting carbon cloth to shape, assembling in jigs and, finally, bonding the whole with carbon by deposition from a hydrocarbon under conditions that ensure carbon deposition throughout and continuing with the process until the component is adequately dense. The nature of the process means that there is inevitably some residual porosity which is typically 5–10 %. The matrix consists of crystallites of carbon which are themselves oriented by virtue of their growth around each fibre and thus subscribe to the anisotropy of the disks. An electron microscan of a fracture surface is shown in figure 6 (plate 1).

The manufacturing process for a large and thick part takes typically four months and hence the production batch consists of many hundreds of brake disks.

Material evaluation and quality control

A major part of the development has been directed towards parametral studies, design changes of an iterative nature, property and process variable evaluation. The quality control exercise has been directed towards tests which are relevant to the product and its use and at the same time can be performed readily and repeatedly. Some tests are carried out on complete disks while, for others, sample disks are cut up and subjected to more detailed examination. The reinforcing cloth is made to a tight specification but presents the problem that its properties cannot readily be related to carbon carbon composite properties.

Theoretical studies using heat flow and stress finite element programmes have been made but, although the disk shapes are regular, the anisotropy of the disk and heat input variation make the task a formidable one.

The studies naturally included thermal diffusivity assessment, techniques for which were developed with U.K.A.E.A. and physical property measurements at 1000 °C. The anisotropy and Poisson ratio had to be determined for modelling purposes. Local measurements of bulk density were needed to determine variations in density within disks and a γ-ray absorption technique was developed.

For detection of variations within a disk, particularly of delamination, thermal imaging, automatic scanning by ultrasonics, and X-ray techniques were examined. For study of failure

FIGURE 6. Electron microscan of a fracture surface of a carbon carbon composite (× 1424).

mode under various loading and repeat loading patterns acoustic emission methods were tried. A number of these studies were made with the co-operation of A.W.R.E., Aldermaston. Variables such as fibre type, shape, fibre volume fraction, form of lay-up and chemical purity were also studied.

Development objectives

To improve the carbon carbon composite material the development objectives can be readily defined. They are to achieve:

(i) an increase of specific strength;
(ii) a greater strain to failure;
(iii) an increase in static friction coefficient;
(iv) a cheaper product.

Because weight saving was the reason for the adoption of carbon carbon composites for brakes, one would be reluctant to add weight in order to achieve strength. Strength at the fully worn condition is already a critical design factor. It is therefore an increase in strength per unit weight that is sought. At the same time, volume for the heat sink is critical and hence a high density composite is required. This is a complex function of the process variables. For example the densities of the carbon fibres and the carbon matrix can vary according to the precursor material and the processing parameters.

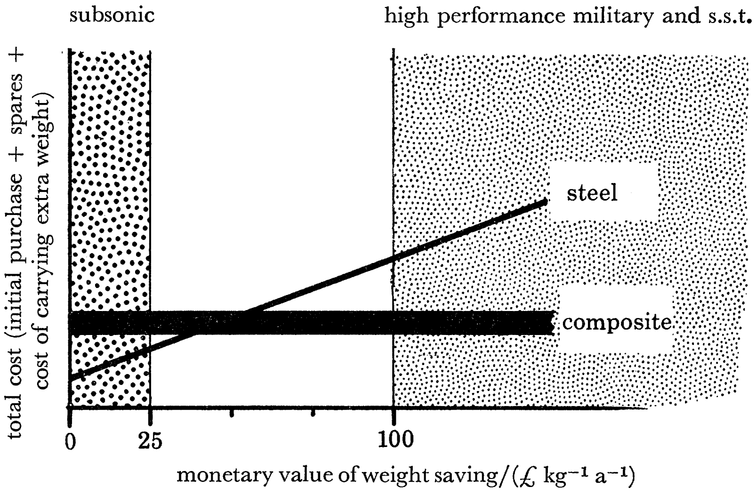

Figure 7. Relative cost effectiveness of carbon carbon composite brakes and steel brakes. The total cost is the sum of the cost of initial purchase, spares and that of carrying the extra weight.

A greater strain to failure would provide a tougher material which in turn would be less sensitive to the maldistribution of both mechanical and thermal loading.

The static coefficient of friction of carbon carbon composite is unusual in that it tends to be less than the normal landing dynamic coefficient, 0.15 compared with 0.20–0.35. The use of sintered iron type friction material usually causes a brake to develop a static coefficient in the range 0.25–0.35 and a normal dynamic one of 0.18–0.27.

A high brake pressure is required to achieve the aircraft static drag requirement with a carbon brake and this pressure could be applied while the aircraft is in motion, with resultant unwanted high torques. This situation would be avoided if an increased static friction coefficient could be provided.

The composite is expensive. Initially it was of the order of £550/kg. More recent designs of composite promise to be about one fifth of the initial value. If a further reduction by a factor of two can be achieved, the carbon carbon composite brake is likely to find an extensive market.

Figure 7 illustrates the choice for an aircraft operator. In determining whether the weight saving of a carbon brake is commensurate with the additional cost of the material, there is a need to determine the value of weight saving per pound per annum. The ordinate shows total cost, i.e. the cost of initial purchase, spares and in the case of the steel brake the cost of carrying its extra weight – the carbon brake is taken as the weight reference.

Opinions as to the value of weight saving to operators differ widely. However, it is clear that civil subsonic aircraft should be grouped quite separately from supersonic transports (s.s.t.) and high performance military aircraft.

Concorde is said to justify a value of weight saving of £500/kg/annum.

CONCLUSION

The design of the carbon carbon composite when used for brake disks is primarily determined by requirements of strength, heat flow and manufacturing costs. The design of the brake has to accommodate the variation in friction and wear properties.

Development activities have proceeded along three main lines, first the engineering of the installation and the performance of the equipment, secondly the manufacturing and process variables and thirdly, those related to new concepts. The pressing need to achieve repeatability of properties has been recognized and has become a common factor in all functions of development.

The potential for further design changes in the composite and within the brake structure is substantial and the prime development target is to produce cheaper carbon carbon composites.

The striving to achieve cheaper carbon carbon composites has already reached a stage where civil subsonic aircraft constructors feel the need to gain first hand experience on their aircraft and to further encourage the brake industry. Requests have been made that carbon carbon composite brakes should be made for certain subsonic civil transport aircraft and eventually be fitted to these aircraft in service in order to obtain practical experience. This is not a cheap exercise. Concorde has approximately 300 kg of composite in its eight brakes. Qualification testing prior to fitment on an aircraft is extensive.

The cost of supplying equipment for a demonstration of carbon carbon composite brakes on one large aircraft would be in excess of £½M.

REFERENCES (Stimson & Fisher)

Barber, J. R. 1969 *Proc. R. Soc. Lond.* A **312**, 381.
Kennedy, F. R. Jr & Ling, F. F. 1973 *ASME*, paper 73, LUB 6.
Stimson, I. L. & Dowell, F. S. 1973 *Society of Aeronautical Weight Engineers*, paper 995.

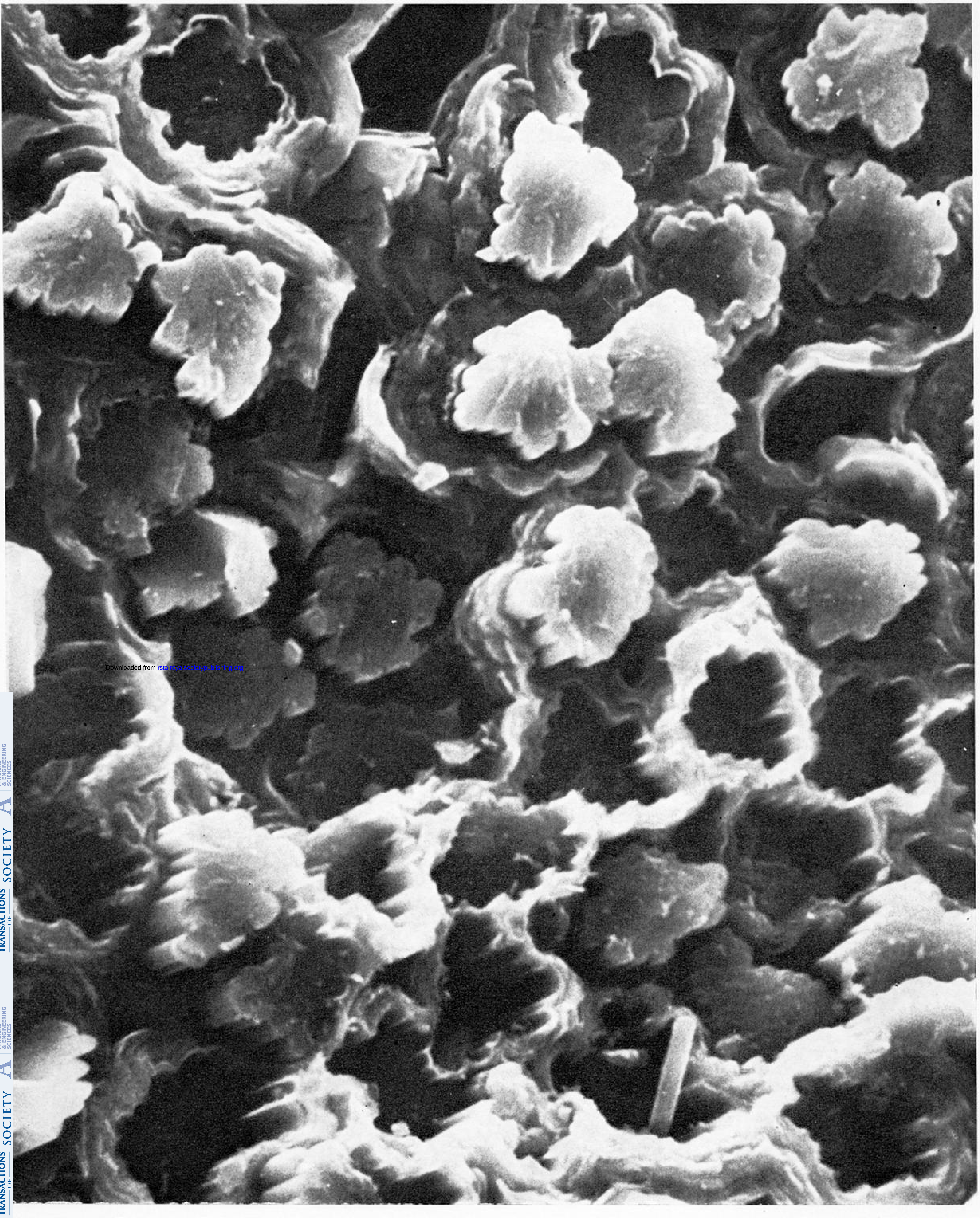

FIGURE 6. Electron microscan of a fracture surface of a carbon carbon composite (× 1424).