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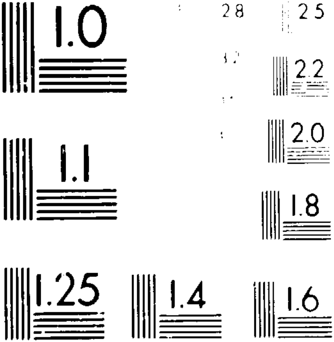

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CARBON FIBRES AND THEIR APPLICATION*

by

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TECHNICAL STATUS AND FUTURE PROSPECTS OF CARBON FIBRES

1. The nature of carbon fibres

Carbon fibres are very thin fibres, much thiner than human hairs. They have diameters between 6 and 10 µm, in American units a quarter of a mill. They are also thiner than glass fibres which correspond in thickness to that of human hairs and which are used so far for reinforcement of polymers.

Carbon fibres consist to 99,9 % of chemically pure carbon. They are not chemical compounds or alloys such as conventional structural materials, for instance steel or aluminum, which always contain small amounts of alloying elements.

These black thin man made fibres - inbedded in polymers - have initiated a "revolution in materials". Even popular magazines do report on this "wonder material". Such "advanced composites" contain up to 60 v% of carbon fibres. We will discuss what extraordinary properties of carbon fibres justify such [illegible], especially in view of [illegible] with glass fibre reinforced composites.

If compared with fibre glass, advanced [illegible]
[illegible]

strength. Due to this combination, first time polymer materials became a competition for metals in structural application.

Advanced composites have further advantageous properties, such as extremely low thermal expansion, better fatigue resistance and (not mentioned in the figure) high corrosion resistance.

The key properties for reinforcement fibres used today in composites with polymer matrix for reinforcement - the tensile strength and the YOUNG' s modulus - are compiled in Fig.4. Glass fibres, especially R- and S-types which have a high Al_2O_3-content, have high strength (above 2000 to 3500 MN/m^2) but low YOUNG's modulus (below 100 GN/m^2). Polyaramide fibres (KEVLAR® from DuPONT or ARENKA® from ENKA) are organic fibres with improved YOUNG's modulus up to 150 GN/m^2.

Only the family of carbon fibres covers a range of YOUNG's modulus values between 200 and 500 GN/m^2 and strength data from 2000 to 4000 or even 4500 MN/m^2. Within this product family we distinguish between " PAN based" and "pitch based" carbon fibres. Only the mesophase pitch based carbon fibres are used as reinforcement fibres, whereas the isotropic pitch based fibres (KUREHA carbon fibres) have only applications as insolation materials,as filler and for some other purposes.

Within the PAN based carbon fibres we find the large group of high tensile strength fibres with only medium high YOUNG's modulus between 200 and 300 GN/m^2 and the so-called high

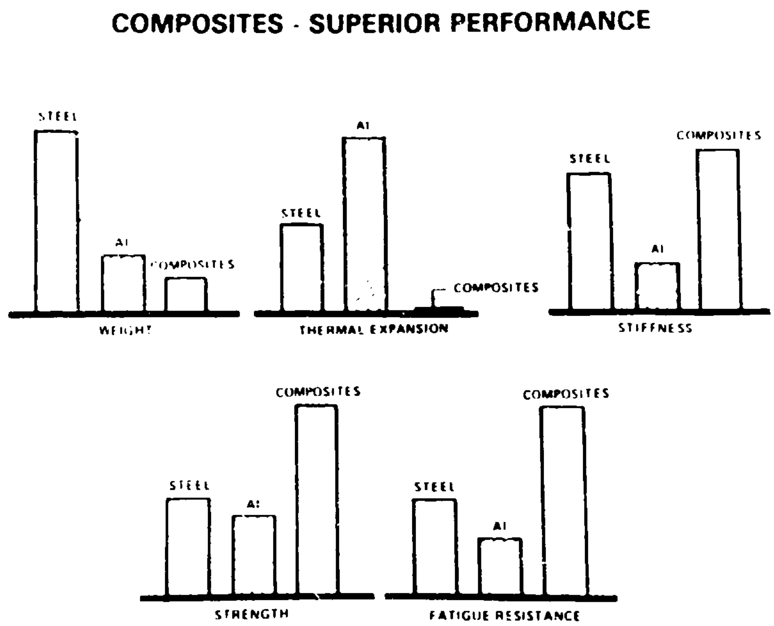

Fig. 3 Superior properties of advanced composites as compared with conventional metals (3)

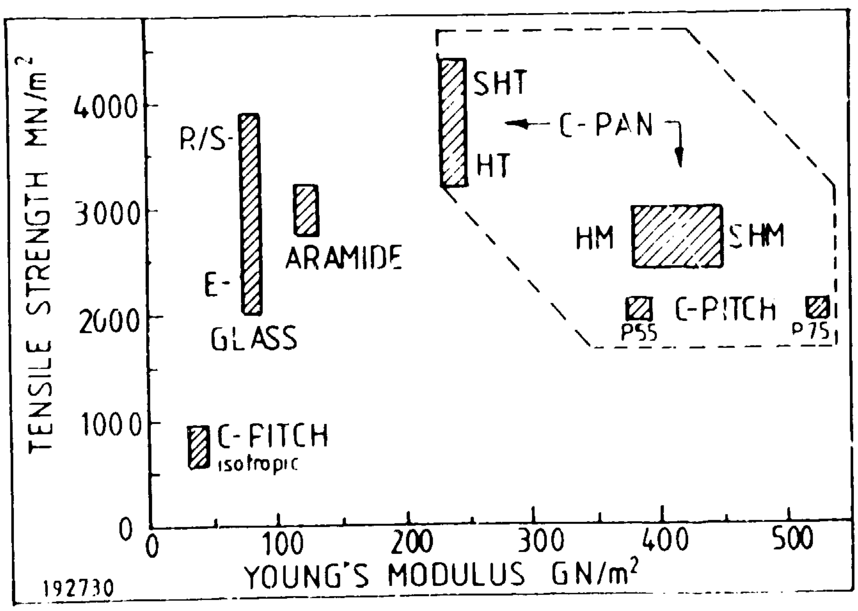

Fig. 4 Tensile strength and YOUNG's modulus of the various fibre types applied for reinforcement of composites

modulus fibres with YOUNG's modulus values above 400 GN/m^2. Extra qualities such as super high tensile strength (SHT) and super high modulus types (SHM) are also PAN based.

The "mesophase pitch based fibres" reach very high modulus values but low strength of around 2000 MN/m^2 only.

Today's and future broad application of carbon fibres as structural material is mainly based on the high tensile type with much higher strain to failure if compared with the high HM types and especially with the pitch based ones. High modulus fibre types are used today for very special applications only, where such high modulus is effectively needed.

Recognizing these surprising high mechanical properties of carbon fibres, we have to consider three questions:

1. What is the reason for the extremely high YOUNG's modulus and the high strength ?
2. How can be explained the broad variety of these properties in the family of carbon fibres ?
3. Can all of these modified types be produced under reproducible conditions ?

ad 1.)

The high strength and especially the high YOUNG's modulus are caused by the very strong chemical bond between the carbon atoms within the graphitic layers, that means in crystallographic a-direction. These anisotropic bonds are based on the sp^2 hybridization of the carbon atoms in this structure. The structure of graphite (see Fig. 5) is known since nearly 60 years, after it was correctly described first time independently but nearly simultaneously by both H. MARK (4) and J.D. BERNAL (5). The very dense packing of the carbon atoms within the layers can be seen from the left part of Fig. 5, whereas on the right side the usual demonstration of lattice structures with only lattice places instead of atoms has been used for better recognizing of the lattice distances.

Since at about 10 years the dense packed layers became visible by high resolution transmission electron microscopy. Fig. 6 shows such an image of highly graphitized carbon in direction of the layer planes.

As known, the bond strength between the atoms controls directly the lattice elasticity. The high strength of the bonds between C-atoms in the layers is due to the homopolar nature, whereas the Van der Waal's type bonds between atoms of neighbouring layers is the explanation for the lower strength in this lattice direction. The high electrical and thermal conductivity of graphite in direction parallel with the layers is caused by delocalized electrons between the layers. Graphite single crystals, however, can not be described as a metallic conductor, but only as a semi conductor

The elastic constants are known with quite high precision for graphite single crystal (6). Fig. 7 shows the most important three elastic constants, C11, C33 and C44. In case

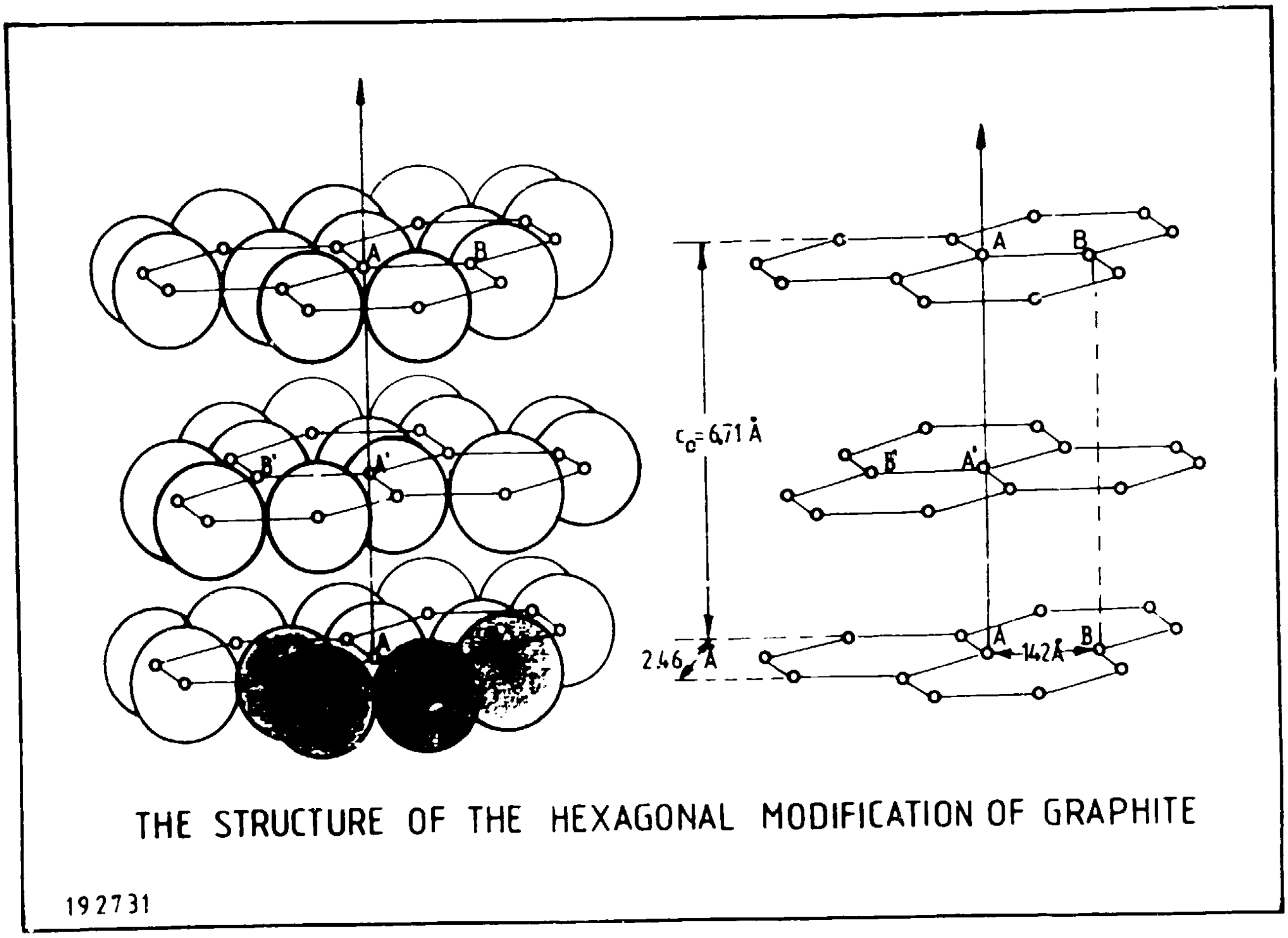

Fig. 5 Graphite structure (4,5)

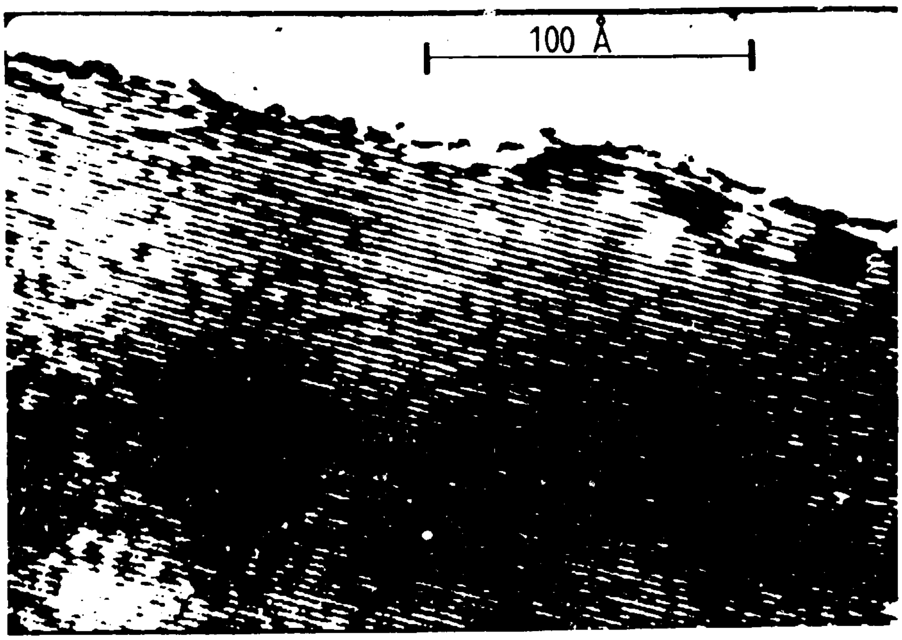

Fig. 6 High resolution TEM of highly graphitized carbon

of complete prefered orientation of the layer planes parallel with the fibre axis the maximum theoretical value for the YOUNG's modulus would be 1060 GN/m^2, whereas the modulus perpendicular to the fibre direction can be expected as being an order of magnitude lower. The lowest value can be seen for the shear modulus C44.

ad 2.)

The consequences from knowledge of these elastic constants of the graphite single crystal in view of useful carbon fibres for reinforcement purposes are :

a) highest YOUNG's modulus and strength in carbon fibres will be obtained by highest prefered orientation, and

b) the easy shear between the layers as in the ideal graphite lattice must be avoided.

The different degrees of realization of both demands causes the broad variety of carbon fibre qualities.

ad 2a)

Fig. 7, right hand side, shows the correlation between measured YOUNG's modulus in various carbon fibres and degree of prefered orientation, as determined by X-ray diffraction. In best cases, values up to 70% of the theoretical maximum values have been achieved already in available carbon fibre types. It shows also, that medium YOUNG's modulus values (around 250 to 300 GN/m^2) as for HT type fibres are combined with incomplete prefered orientation.

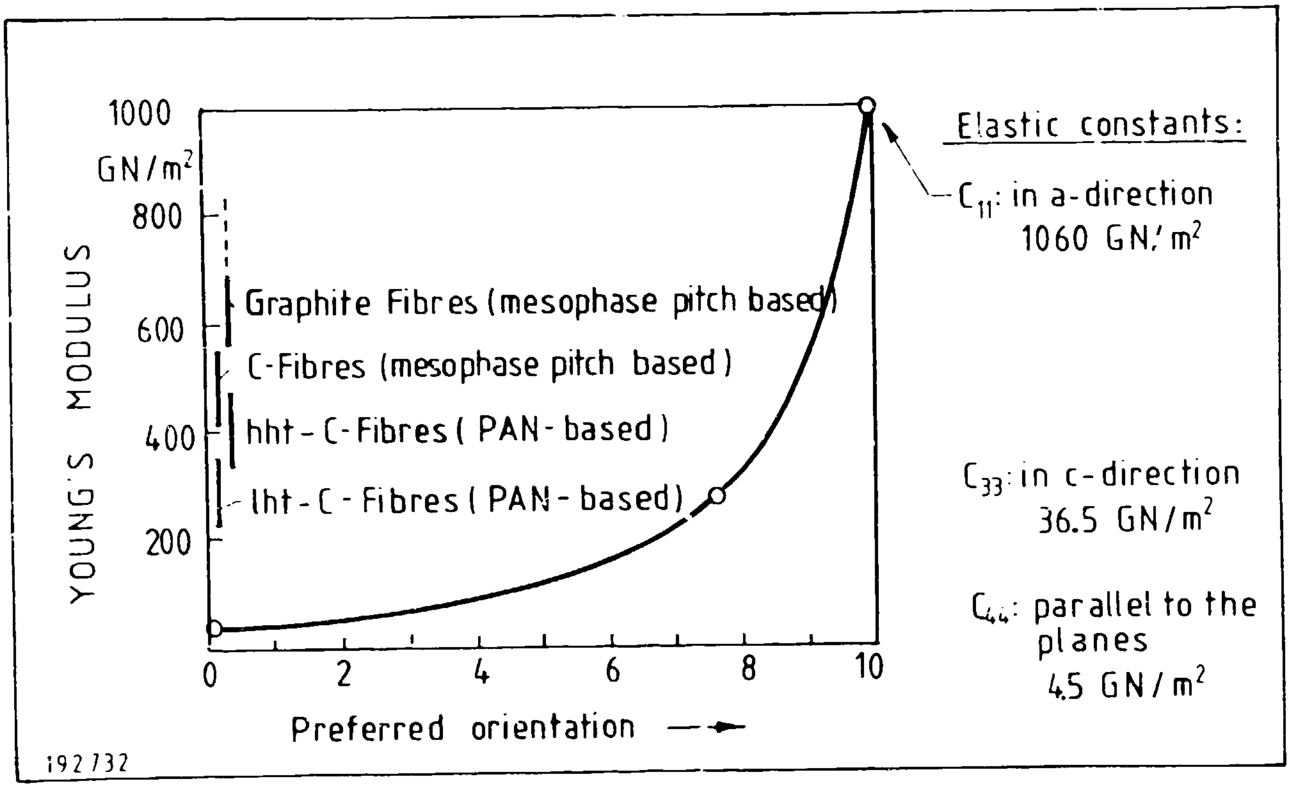

Fig. 7 Elastic constants of graphite (6) and effect of prefered orientation on YOUNG's modulus of C-fibres

Fig. 8 Bent single crystal of graphite (7)

ad 2b)

Fig. 8 shows a single crystal of graphite (7). In spite of the high strength within the graphite layers, the crystal can easily be bent because of the very low shear modulus. The introduction of lattice defects will avoid this shear between the layers.

Fig. 9 shows the various types of lattice defects in a graphitic structure, namely defects within the layers, defects between the layers, mostly stacking faults which cause higher lattice distance, and finally disclination of the layers. The both first defects are mostly combined, that means defects within the layer cause stacking faults and higher lattice distances. By these defects incomplete delocalization of the π-electrons is caused and shear between the layers is hindered. In case of disclinations shear can be hindered from geometrical viewpoint. But in this case, also defects within the layer and stacking faults must be combined with the disclinations. Otherwise, disclinations can act as a crack initiator (8). X-ray diffraction gives an indication of defect free distances within the layers. These areas of coherent diffraction behaviour vary between 20 and some hundreds Å and depend strongly on precursor type, stabilization condition and the final heat treatment temperature between 1400 ^{o}C and 2700 ^{o}C.

Some of the lattice defects can be demonstrated by high resolution transmission electron microscopy (see Fig.10). Prefered orientation and disclinations are mainly introduced by the polymer fibre itself, that means by the

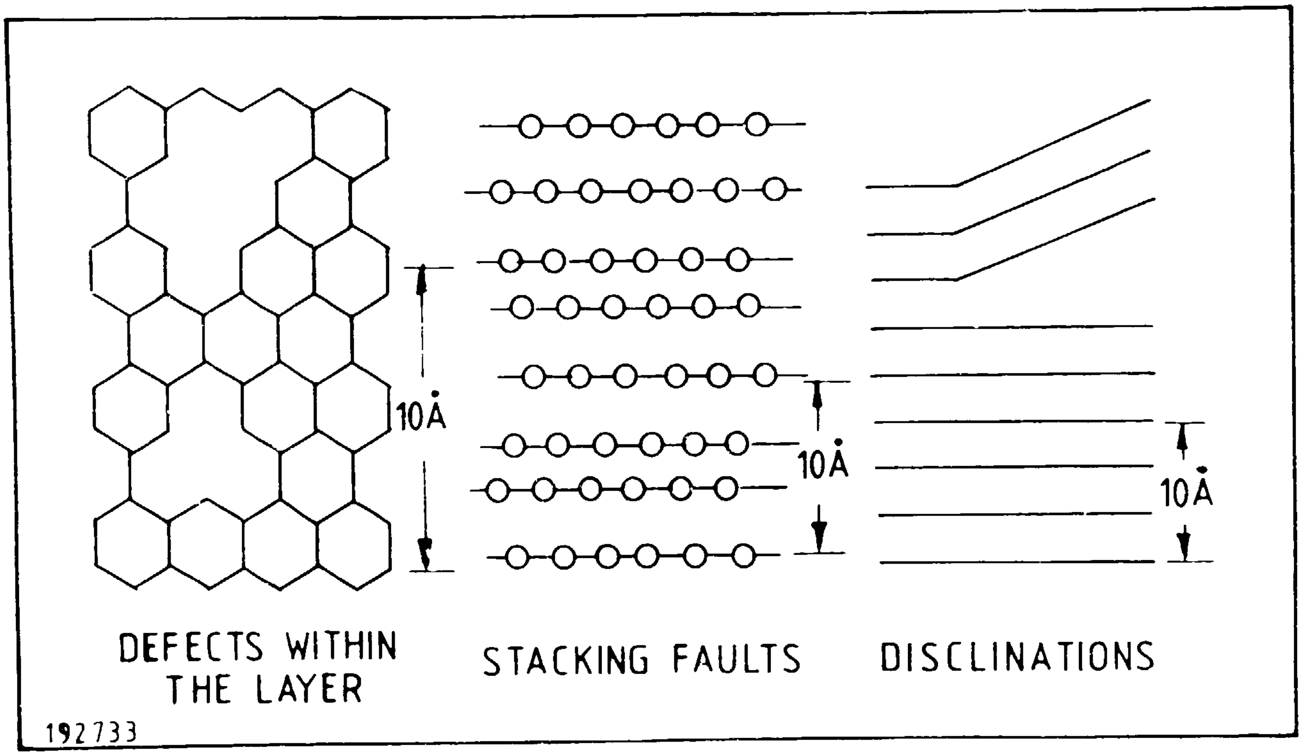

Fig. 9 Lattice defects in carbon fibres

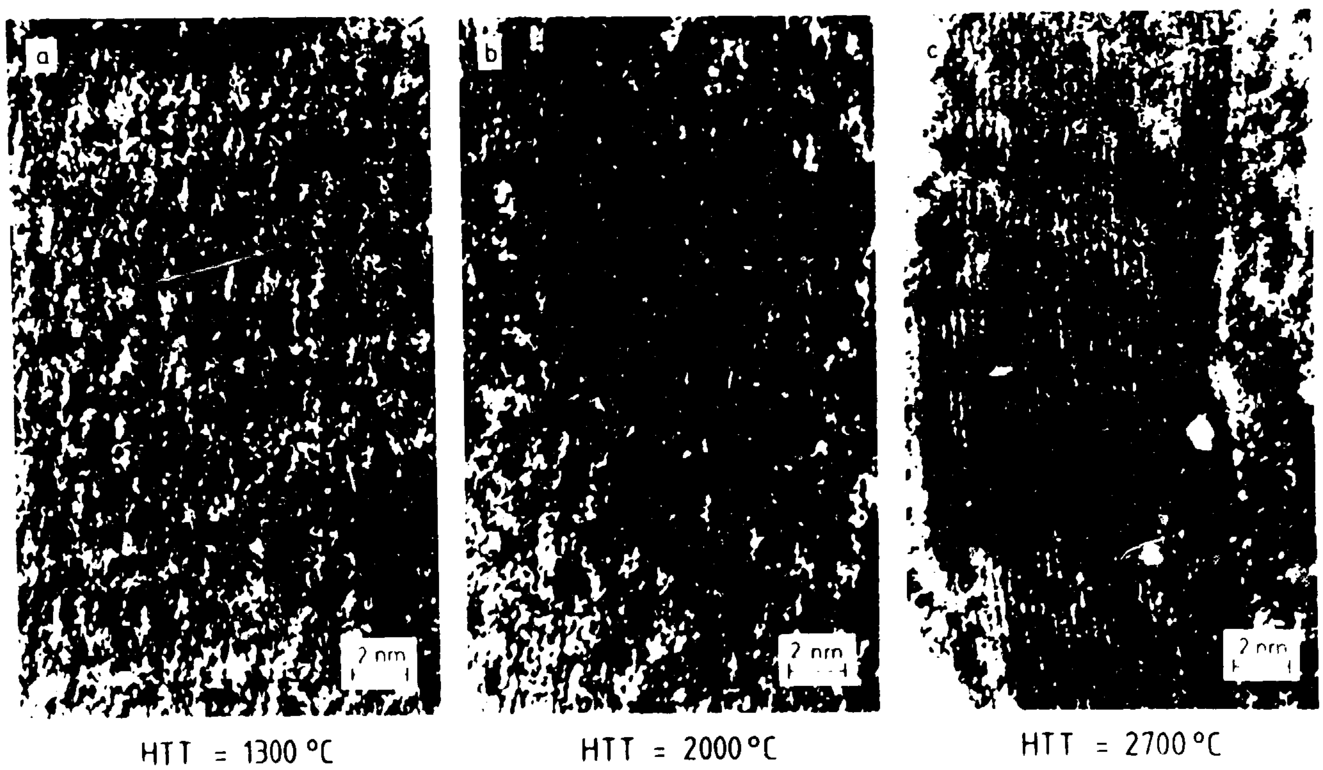

Fig. 10 High resolution TEM of PAN based carbon fibres after various final heat treatment

applied textile prestretching and the degree of stress during stabilization. Stacking faults and defects within the layers are mainly healed by heat treatment up to graphitization temperature. However, in PAN based fibres real graphitization has never been found. That means, annealing of most stacking faults and complete delocalization of π-electrons can not be achieved (Fig. 13).

It is understandable, that the progressing growth and improved orientation of the layers will increase the YOUNG's modulus in fibre direction. In former years, this perfection in prefered orientation and healing of lattice defects was combined with a decrease in strength. Newest fibre types have shown, however, that in case of using very pure polymer precursor which results in pure carbon fibres, the strength found at 1300 °C will not be reduced during high temperature heat treatment up to 2700 °C. The lattice defects in the carbon fibre are controlled by the structure of the polymer already, under the precondition, that carbonization will not pass a liquid state. PAN, a thermoplastic polymer, has to be transformed therefore into a non melting ladder polymer by cyclization and cross linking oxidation before carbonization (stabilization treatment). Carbon, resulting from such a cross linked polymer is called "polymer carbon".
The mesophase pitch based fibres show always best perfection of the graphitic structure and therefore highest tendency for graphitization resulting in formation of sheet like structural elements. An example is shown in Fig. 11 representing the fracture surface by REM. It is assumed that the fracture is initiated by graphitic structural planes (8).

Another indication of shear sensitivity because of beginning graphitization is demonstrated in Fig. 12 by means of the torsional fracture surfaces (9). The increased fracture surface of high modulus fibres (middle of the figure) can be recognized if compared with that of the high tensile carbon fibres (left hand side). The fracture surface of mesophase pitch based carbon fibres (right hand side) is extended by an order of magnitude because of the low resistance against shear.

From scientific viewpoint this result is not surprising because mesophase pitch is the ideal precursor for best graphitizing carbons. The needed structural defects within the resulting carbon must be introduced during oxidation treatment of the pitch fibres, similar as during stabilization treatment of PAN. Contrary to the ladder or even step ladder structure of oxidized PAN, oxidized mesophase will retain sheet like polyaromatic structures with less degree of defects. The task to form non graphitizing carbon from a pitch mesophase is an intrinsic contradiction.

Fig. 11 SEM image of cut phase of mesophase pitch based carbon fibre showing internal sheet like structure (8)

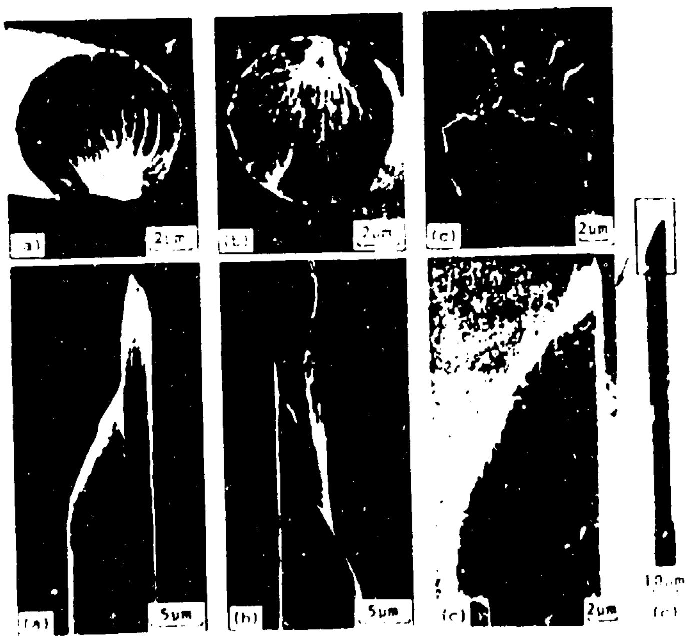

Fig. 12 Torsional fracture surfaces of carbon fibres (9)

a) PAN based low heat treated

b) PAN based highly heat treated

c) Mesophase pitch based

2. Today's properties of carbon fibres and possibilities for further improvement

2.1. Nomenclature

It was shown before, that the mechanical properties, these are first of all YOUNG's modulus and tensile strength of the C-fibres depend on the precursor material as well as on the final heat treatment. For characterization of the various types of C-fibres we need therefore an indication of both parameters. The nomenclature varies in different countries because of traditional reasons.

The British group who has developed the carbon fibres on PAN basis uses for highly heat treated fibres (heat treated at graphitization temperatures) the term type I-fibres. They understand under type II-fibres carbon fibres which have been heat treated around 1400 °C maximum only.

The American industry prefers the term "carbon fibres" for the fibres according British nomenclature type II and the term "graphite fibres" for the highly heat treated fibres corresponding British nomenclature type I.

As recommended by IUPAC (10), however, the term "graphite" can only be used, if carbon material with crystalline order in c-direction is considered. Such crystalline order is never achieved in highly heat treated PAN based carbon fibres. Therefore, the term "graphite fibres" should not be used. The variety of carbon fibres can also be characterized by the fibre properties: "high tensile" type (HT) and "high modulus" types (HM). So far as PAN is used as precursor, high tensile type corresponds to final heat treatment temperatures around 1400 °C and high modulus fibres to those of at about 2500 to 2700 °C. This description by means of properties became difficult for pitch based carbon fibres. There does not exist a high strength fibre but only high modulus types, even if heat treatment has not exceeded temperatures of 1800 °C, whereas heat treatment at graphitization temperature will result in ultra high modulus fibres. Also some crystalline order in third direction can be observed, especially if stabilization treatment (oxidation before carbonization) was incomplete and the term "graphite fibres" would be justified for some grades of these carbon fibre types (Fig.13).

There exists another fibre type recently developed by Japanese workers (11) which deserves the use of the term "graphite fibres" from scientific viewpoint. These are the fibres grown by gas phase deposition on fine dispersed catalysts. They are effectively graphitizable, and if highly heat treated, they exhibit excellent graphite structure. According to the theoretical considerations discussed above, they are completely unsuitable strengthening fibres, but interesting for electrical application, especially because of their suitability to form intercalation compounds.

The following new terminology is in discussion by IUPAC (12): All carbon fibres used for reinforcement of polymers are PAN based carbon fibres. It seems unnecessary, therefore, to indicate the precursor additionally. The heat treatment can be described by small indices letters additional to the term "carbon fibre" such as "hht" meaning highly heat treated, or " lht" meaning low heat treated. Pitch based carbon fibres represent a completely different group of carbon fibres. So far as they are used for structural application, they should be described by the used precursor, namely as "mesophase pitch based carbon fibres". If they are highly heat treated, they will graphitize partially. In this case, one can use the term "mesophase pitch based graphite fibres". The pitch based carbon fibre - types used for thermal insulation or as filler material can be described as "isotropic pitch based carbon fibres.".

2.2. Mechanical properties of today's carbon fibres

Fig. 14 shows stress strain behaviour of the various fibres. Within the PAN based as well as the mesophase pitch based carbon fibre group the YOUNG's modulus reaches maximum value with highest heat treatment temperature, which is indicated

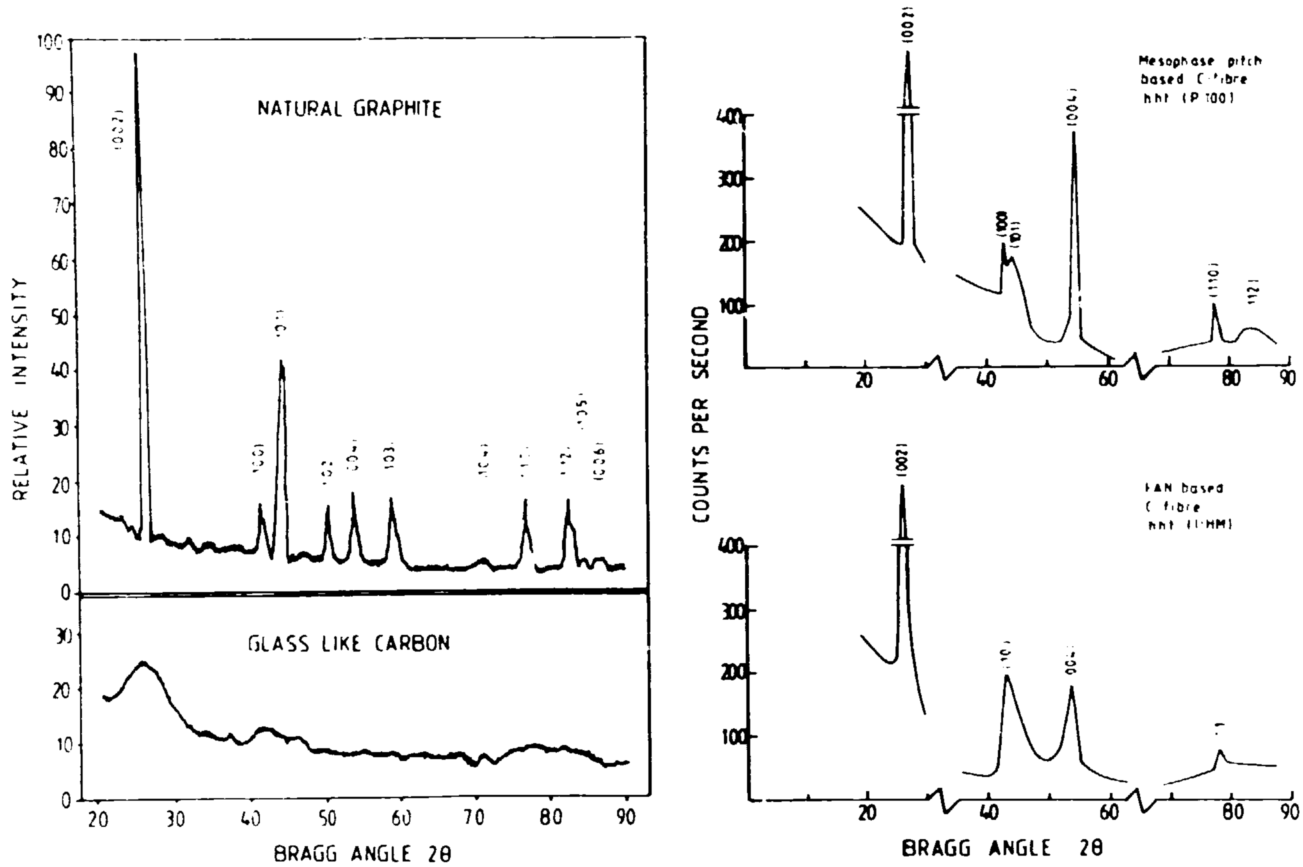

Fig. 13 X-ray diffraction profile of graphite single crystal, mesophase based carbon fibre P 100 (partly graphitized), PAN based UHM carbon fibre and glass like carbon, last both representing polymer carbon in spite of heat treatment at graphitization temperature

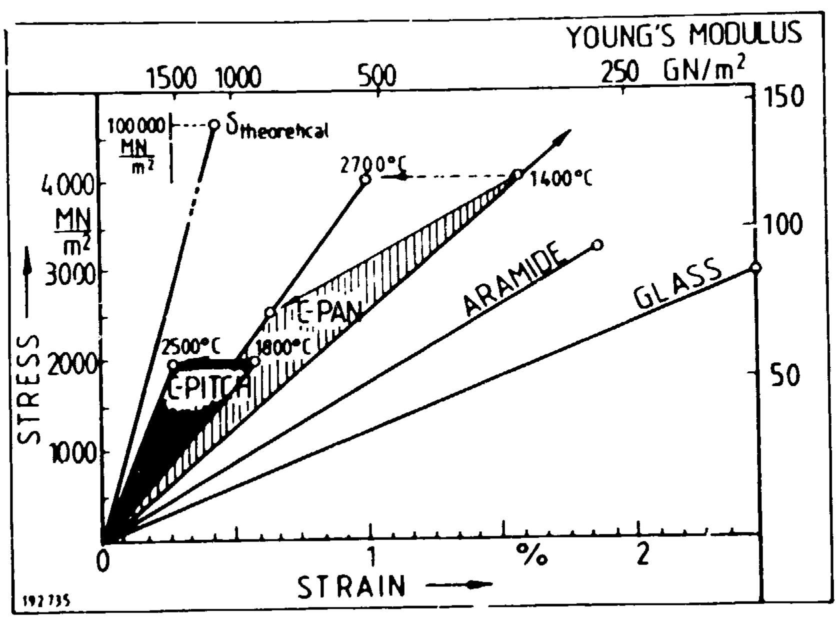

Fig. 14 Stress strain behaviour of the various reinforcement fibres.

by the left boundary of the property fields. The right boundaries correspond to the lowest applied heat treatment temperatures. The most important carbon fibre grade for application in structural elements such as in aerospace, machinery, sporting and so on, is the PAN based type low heat treated (1400 °C) one with strength values of 4000 MN/m^2 and increasing strength tendency as indicated by the arrow. The most important advantage of this group is their high value of strain to failure. The future development of all fibre producing companies is directed to achieve products with even higher strain to failure values, but preserving the same medium high modulus (250 to 300 GN/m^2) (compare also Fig. 19).

The very low strain to failure of high modulus fibres and all types of pitch based carbon and graphite fibres is only tolerated if the very high YOUNG's modulus is absolutely needed. In carbon/carbon composites (these are fibre reinforced all carbon composites with carbon matrix instead of polymer matrix), these high modulus types and even more the pitch based carbon and graphite fibre types are most advantageous.

2.3. Considerations on mechanical properties which can be expected in future

The YOUNG's modulus for perfect prefered orientation and defect free layers is known from the elastic constant C 11 with 1060 GN/m^2 (see Fig. 7). Such theoretical stress strain behaviour is included in Fig. 14. Ultra high modulus carbon fibres have a YOUNG's modulus which corresponds to 70%, in some laboratory scale samples already to 80 %, of this theoretical maximum value.

Minimum still tolerable fracture toughness for practical application of these fibres can be achieved only, if the strength would be increased drastically. There exist some theoretical considerations on maximum strength of a material depending on the YOUNG's modulus E, surface energy "γ" and lattice distance "a" according to the relation: $\sigma_{theor.} \sim \sqrt{\frac{E \cdot \gamma}{a}}$
For carbon fibres with perfect prefered orientation and defect free layers the theoretical strength can be expected as 1/10 of the YOUNG's modulus value, that is 100 GN/m^2. Taking best strength values for the ultra high modulus fibres of at about 2000 MN/m^2, only 2 % of the theoretical maximum strength value has been achieved.

The situation becomes better if we consider high tensile strength values with lower YOUNG's modulus. Lower YOUNG's modulus means imperfect prefered orientation. High tensile strength fibre with a YOUNG's modulus of 250 GN/m^2 and an effective strength of 5000 MN/m^2 shows already 20 % of the theoretically expected strength for such a degree of prefered orientation. It is well known that the reason for the lower effective strength is caused by notches which act as crack initiation.

The critical size of such a notch for initiation of a crack is given by the GRIFFITH relation. For low heat treated C-fibres a critical minimum length "l" of at about 50 µm can be estimated. The probability of notches with critical minimum length will control the effective fibre strength. It decreases with reduced sample size. Therefore, we can expect increase of effective fibre strength with decreased length of the test sample. For the description of the probability for the presence of notches the WEIBULL statistic is found to be suitable for carbon fibres. Fig. 15 shows some values of average tensile strength as function of gauche length in tensile testing (13). As consequence, testing methods for characterization of carbon fibres must be standardized. Mostly, gauche length of 30 mm are used for single filament method, and gauche length of 120 mm for the strand method.

These both different methods are explained in Fig. 16. The strand method uses samples in form of fibre bundles which are fixed by epoxy resin in exact position of prefered orientation The cross section is measured by weigth, length, density and number of monofilaments of the fibre bundle. This method gives directly average strength values of all monofilaments within a yarn.

The monofilament method is restricted to the fracture behaviour of one single filament. This method gives more specific results. An exact determination of the cross section of the fibre is necessary. Mostly, the cross section of a bundle is determined by optical microscopic method and used as basis for strength calculation. The single filament method is more time consuming. The minimum gauche length for the

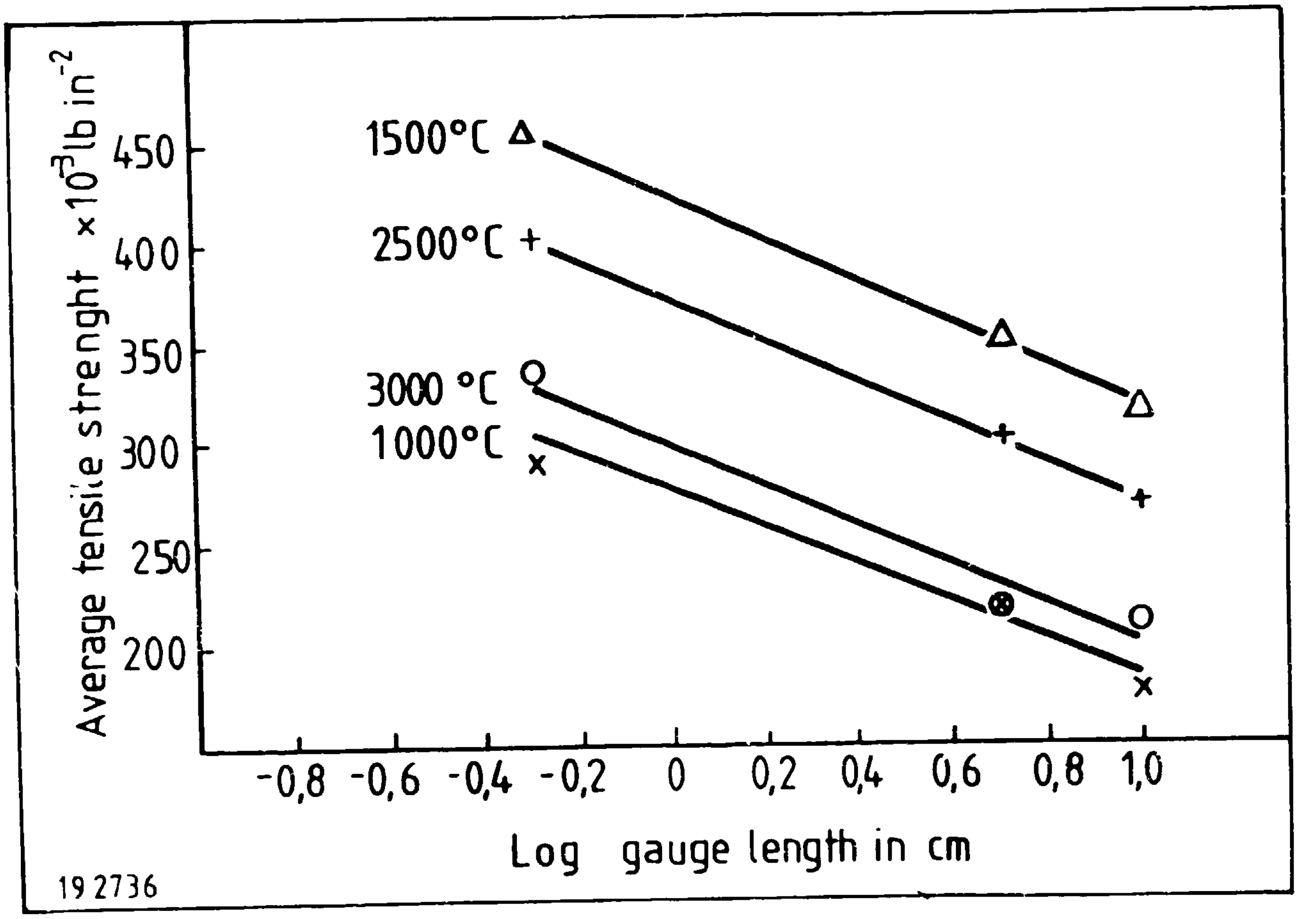

Fig. 15 Average tensile strength of carbon fibres as function of gauche length (13)

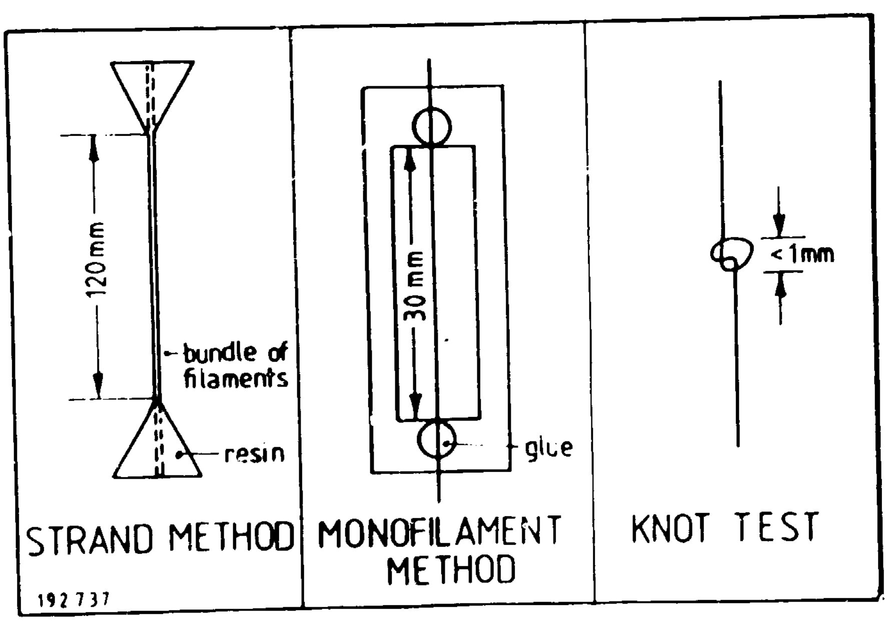

Fig. 16 Methods used for tensile strength test of carbon fibres

single filament method is limited with about 10 mm. For smaller gauche lengthes the knot test must be applied in which the tensile strength is calculated from the diameter of the loop if fracture occurs. Practical gauche length of 1 mm and even less can be realized by this method.

For technical application mostly the strand method is used, because it gives more realistic values for strength of the fibres within the composite. Obviously, the epoxy resin inhibits crack initiation at some critical notches in the fibres, whereas in monofilament tests such a notch acts effectively as crack initiator.

Fig. 17 shows some own results which confirm this finding. The stress strain curves show elastic deformation and fracture of the isolated fibres measured by the monofilament method, of the pure matrix without fibres and of a unidirectionally reinforced composite with 60 v/% of fibres. Dotted lines reflect the behaviour of non surface treated carbon fibres, full lines of surface oxidized fibres. By surface oxidation the strength of the fibre is reduced, but the strength of the composite increased. This is a clear indication, that the notches introduced by surface oxidation are compensated by the epoxy matrix (14).

Before we draw a conclusion from these theoretical considerations we should take a look to table Fig. 18 with the compilation of mechanical properties of some today's commercial fibres, available at least in small quantities. From the

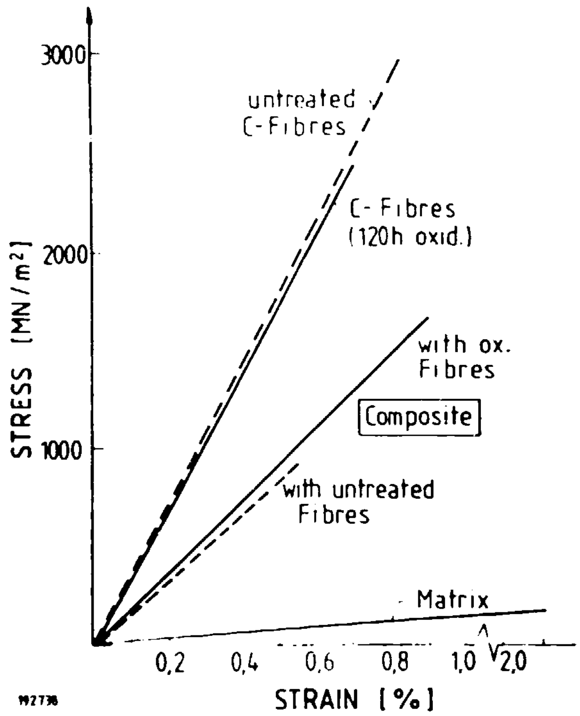

Fig. 17 Stress strain behaviour of carbon fibres, pure matrix material and composite with non surface treated and surface treated carbon fibres. The surface damages by treatment are compensated in the composite by the matrix, which inhibits surface defects (14)

PRODUCTION PARAMETERS		PRODUCER	TYPE	TENSILE STRENGTH MN/m²	YOUNG'S MODULUS GN/m²	STRAIN TO FAILURE %
PAN-based	lht	Toray	Torayca T300	3000	250	1,2
	lht	Toray	Torayca X550	5000	250	2,0
	hht	Toray	Torayca M40	2400 - 3000	400	0,60 - 0,75
	lht	Toho	Beslon ST1	3600	240	1,5
	lht	Toho	Beslon ST2	4080	240	1,7
	lht	Toho	Beslon ST3	4320	240	1,8
	lht	Hercules	IM6	5000	280	1,8
Mesophase PITCH-based	mht	UCC	Thornell P55	2100	380	0,55
	mht	UCC	Thornell P75	2100	520	0,40
	hht	UCC	Thornell P100	2400	690	0,35

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Fig. 18 Mechanical properties of carbon fibres (state mid 1983) viewpoint of design and application of advanced composites, the PAN based "lht carbon fibre" type is most important. Fibres with strength values from 4000 to 5000 MN/m^2 are grades of the so-called "new generation" of high tensile types. The medium level for YOUNG's modulus of 250 to 280 GN/m^2 will guarant a strain to failure up to 2 %. There is a realistic chance for industrial manufacture of them in large quantities. So far, these values can be considered as practically highest quality limit in near future.

Also from viewpoint of compressive strength as well as impact resistance the new generation of "carbon fibre lht" type is superior. It is well known, that all reinforcement fibres with sheet like structure such as polyaramide fibres, but also the "carbon fibres hht" and especially the mesophase pitch based carbon and graphite fibres have a very low compressive strength in a polymer composite. This disadvantageous property is improved with the medium modulus/high strength fibre types.

An additional advantage can be seen in the improved impact strength of composites with this "lht carbon fibres" of the new generation. It was considered always, that impact resistance of a composite with brittle fibres can be improved if pure brittle fracture of the composite is avoided by some delamination and fibre pull-out which stops crack propagation into the fibre. The consequence would be an optimization of the interlaminar shear strength, avoiding extremely high values. The designer, however, likes high interlaminar shear strength.

As found just recently (15), this simple correlation is valid only for high modulus fibres with a very low strain to failure. In case of fibres with high strain to failure, a good adhesion between fibre and matrix, that is a high value of interlaminar shear strength (up to 120 MN/m^2) causes an improved resistance against impact. As explanation is fcund, that the crack propagation in the interface is stopped by elastic defcrmation of the fibre itself if a good adhesion is guaranted. As consequence, increased interlaminar shear strength will increase impact resistance for these fibre types (see Fig.19) (15).

Also this behaviour supports the exceptional position of PAN based low heat treated carbon fibres of this new generation as candidate type for future broad application.

The changes in technology for production of this new generation of lht carbon fibres is not discussed in literature

The first availability of these superior quality fibres was explained by selection of special bobbins from the normal production (16). For controlled reproducible production obviously the following parameters are decisive:

a) low probability for critical notches, that means lower diameter of fibres,

b) very pure precursor fibres,

c) controlled process conditions for spinning, textile pre-stretching and stabilization.

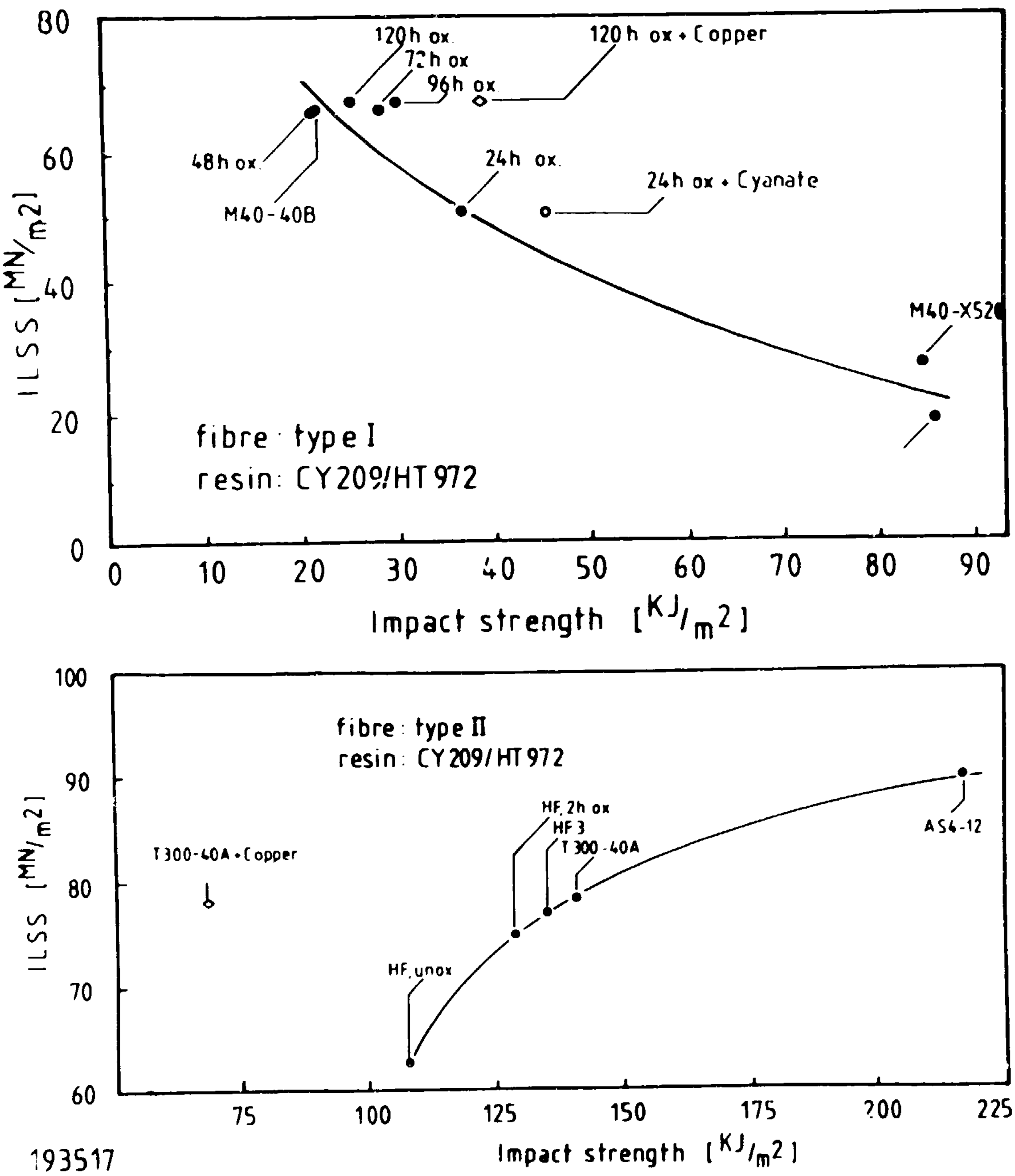


Fig. 19 Correlation of interlaminar shear strength and impact strength of fibre reinforced composites (15)

a) PAN based highly heat treated carbon fibres

b) PAN based low heat treated carbon fibres

3. Economic considerations

High modulus carbon fibres have been introduced for the first time mid of the Sixties to replace boron fibres. The price was in the order of 500 $/kg at least, similar as that of boron fibres. There was a decade long discussion on economy of scale, but the high price level was protected additionally by a latent patent situation.

Mid of the Seventies when the price for the least expensive carbon fibre type was still above 100 $/kg, UNION CARBIDE, USA, started a price war with the introduction or at least the announcement of mesophase pitch based carbon fibres. A price reduction to at least 20 $/kg was promised because of the very low cost of the primary raw material, that is petroleum pitch. From standpoint of reinforcement fibres, today the only final result of this scientifically and technologically most interesting initiative is a radical price breaking of PAN based carbon fibres, down to the level around 35 $/kg, whereas the price for the pitch based types was doubled during last months again. It seems that the claimed low costs of the raw material are compensated by far by the unexpected high production costs, obviously in the process step of spinning. Additionally, the properties of both types of carbon fibres (PAN based on one hand, and mesophase pitch based on the other) are so different, as shown before, that there does not remain any alternative to replace PAN based carbon fibres by pitch based ones, even if economic reasons would justify it.

3.1. Present technology

The fabrication processes for carbon fibres consist of three steps (Fig.20)

The spinning,
the stabilization, and
the carbonization.

Stabilization is an oxidation treatment in air between 200 and 300 °C in order to transform the thermoplastic fibre into a nonmeltable precursor fibre, suitable for carbonization without changing the fibre form. This stabilization treatment needs residence times in the order of 1 h for PAN, but only some minutes for pitch. This behaviour was claimed as a process advantage for pitch fibres. Also the spinning step appeared advantageous for pitch because melt spinning can be applied. All polymer specialists will prefer melt spinning processes, if compared with dry spinning (solution spinning) or wet spinning (solution spinning with subsequent precipitation of the fibres in a coagulation bath). Only melt spinning offers a fast production by cooling without solvent problems and time consuming washing of coagulated fibres. Melt spinning can not be applied for PAN.

Modern polymer technology has developed very economic wet spinning processes based on high multiple spinnerets up to 300 000 holes. Yarns with the same number of monofilaments can be spun in one coagulation bath simultaneously (see Fig. 21). Melt spinning as well as dry spinning are restricted to a maximum of at about 2000 holes in a ring type spinneret.

Fig. 20 Process steps for carbon fibre fabrication

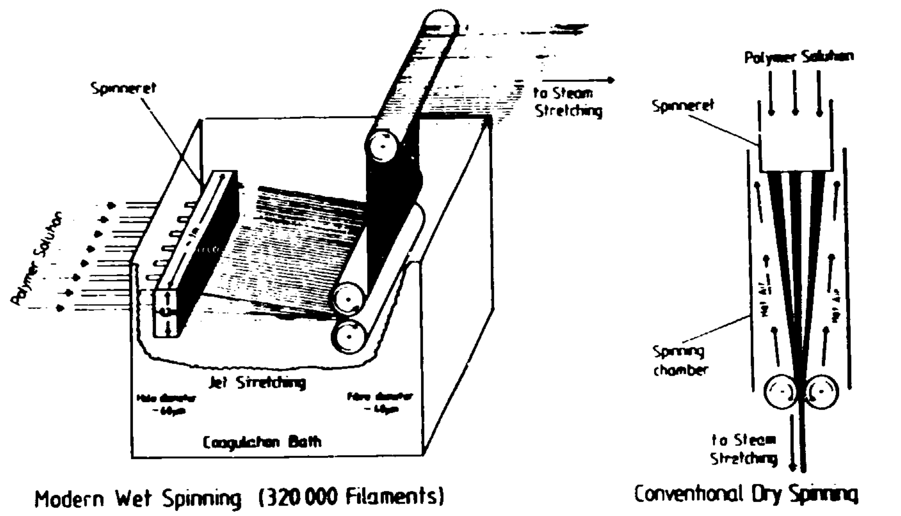


Fig. 21 The spinning of polymers
a) wet spinning
b) dry spinning (similar as melt spinning)

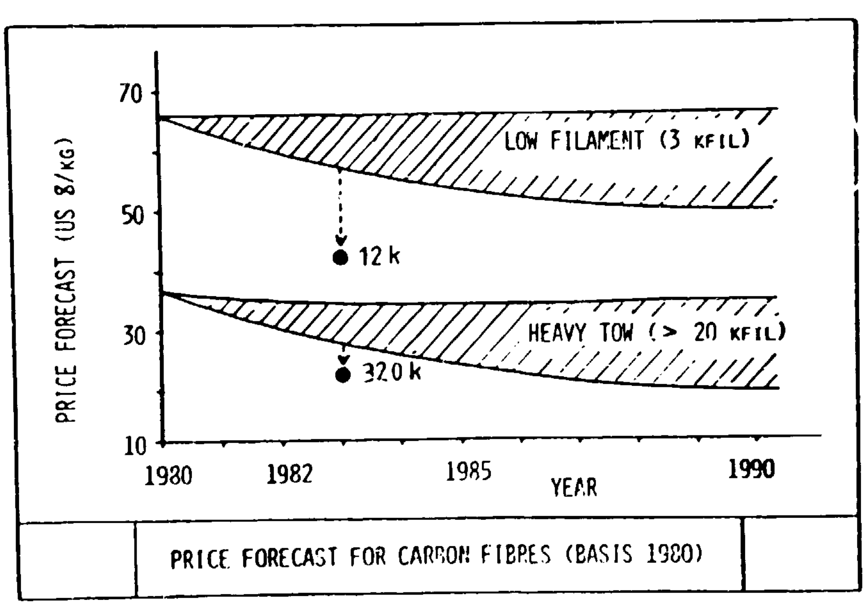


Fig. 22 Price forecast for carbon fibres, basis : 1983

It seems, that all other process steps regarded as more disadvantageous for PAN fibres have less influence for the overall economy of processing than this most economic spinning step. This rationalized spinning, however, demands consequently the application of a multi tow for the carbon fibre production.

3.2. Carbon fibres as heavy tow

This idea to use heavy tow PAN precursor fibres to produce heavy tow carbon fibres is followed only by a few of carbon fibre producers (RK Textile, UK; SIGRI, Germany). The price idea is demonstrated in Fig. 22 . It seems probable, that lowest price limit of heavy tow will be 20 % below the lowest price limit of low filament tow with 12 K.

Strength values of heavy tow as compared with low tow qualities are shown in Fig. 23 (18). All results are obtained with the monofilament method. There do not remain severe differences in strength properties between low filament and heavy tow.

The processing suitabilities of multi filament as compared with low filament carbon fibres are shown in Fig. 24 (18). Multi tow has best chances in application as sheet molding reinforcement, injection molding with staple fibre or rowings, pulltrusion technique as well as wet winding.

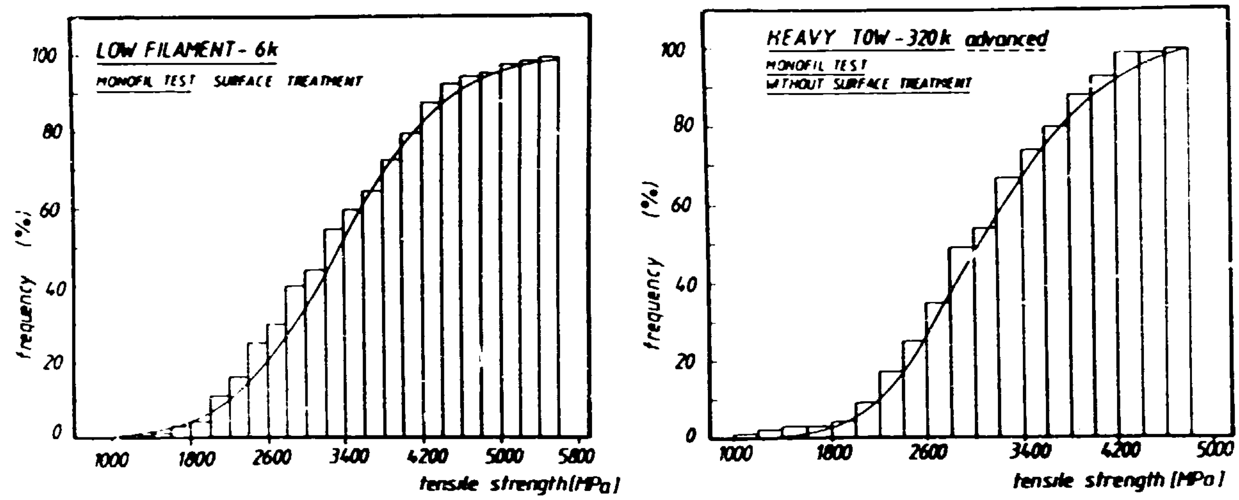


Fig. 23 Frequency of tensile strength in low filament (6000 monofilaments) and heavy tow (320 000 monofilaments) PAN based low heat treated carbon fibres (18)

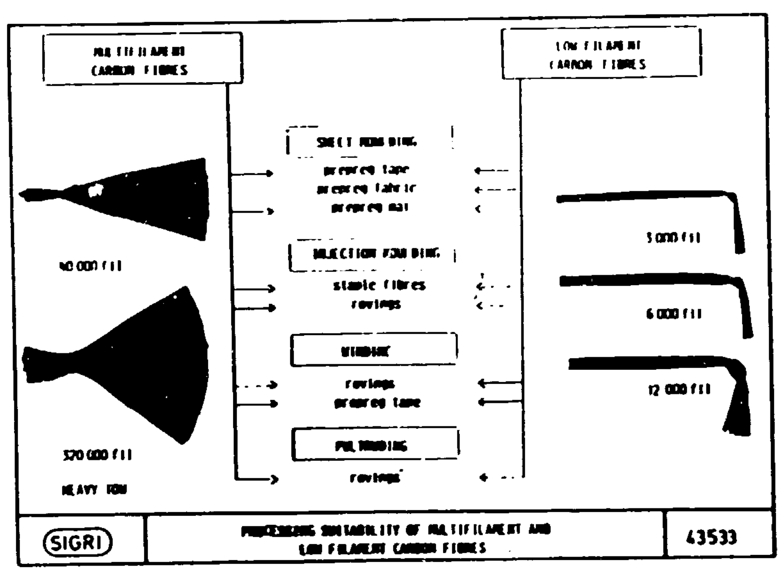


Fig. 24 Processing suitability of multifilament and low filament carbon fibres (18)

3.3. Production capacity, world demand and price development

The total production costs of a material are controlled by

1. raw material costs
2. production costs
3. scale of production

As mentioned before, the problem of economy of scale was taken for justification of high prices since last 20 years. It seems , however, that the year 1982 marks a turn in production scale caused by a steeper increase of world demand (see Fig. 25) (19).

Fig. 25 shows mainly the production capacity of the TORAY group. There are also strong increasing capacities in USA (UCC, HERCULES, COURTAULDS and others) as well as in UK (RK Textile) and in France (Joint venture of ELF / HERCULES / PUK , and again of the TORAY group). There is no doubt, however, that today large Japanese production is mostly export oriented as shown in Fig. 26 (20). Additional advantage for the Japanese producer is the permission of international aviation control organisations for the use of TORAY products in commercial aircrafts based on long year tests.

4. Application of carboh fibres

It is difficult to get exact newest information on the end use distribution of carbon fibres and it is even more difficult to learn about the amount needed for military applications.

Fig. 27 shows latest publication (20), which is concerend on 81 data only. At that time there were two groups of main

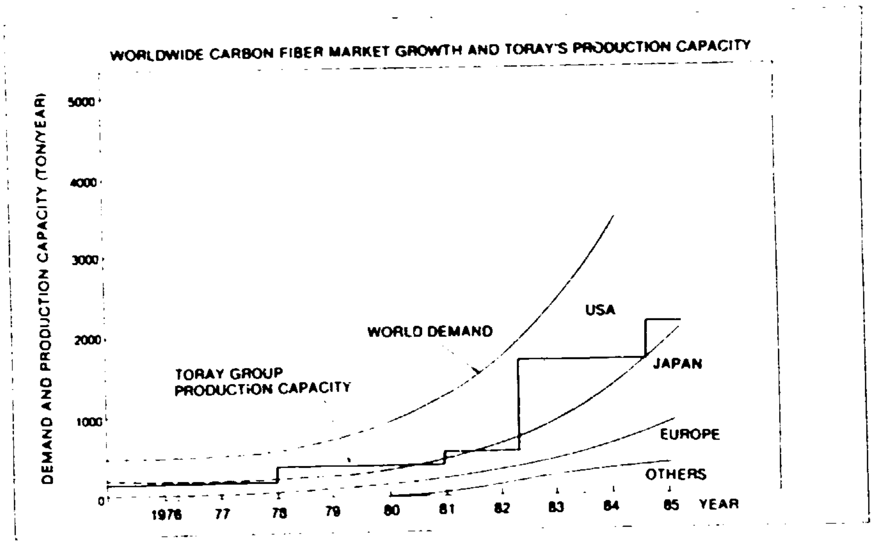


Fig. 25 World wide carbon fibre market and production capacity of the TORAY group (19)

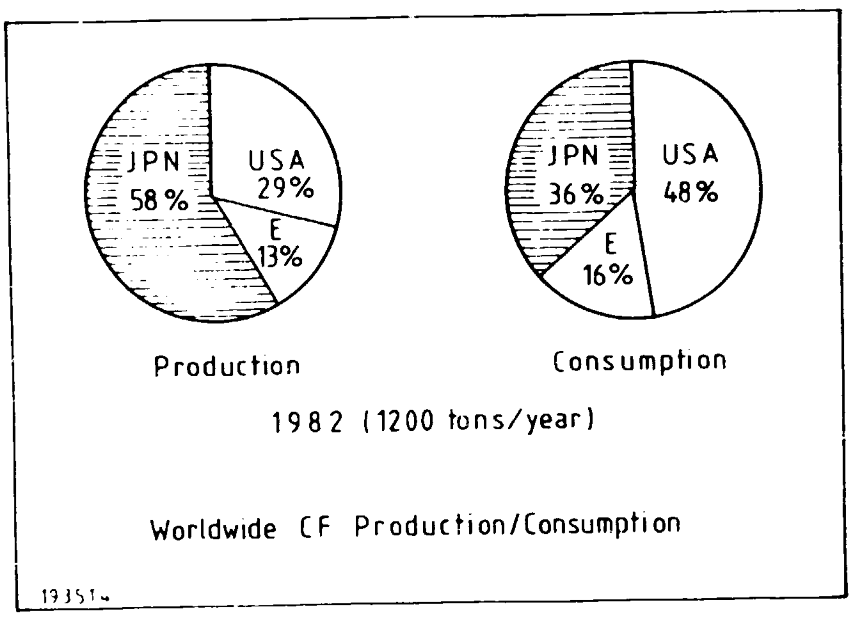


Fig. 26 World wide carbon fibre production and consumption (20)

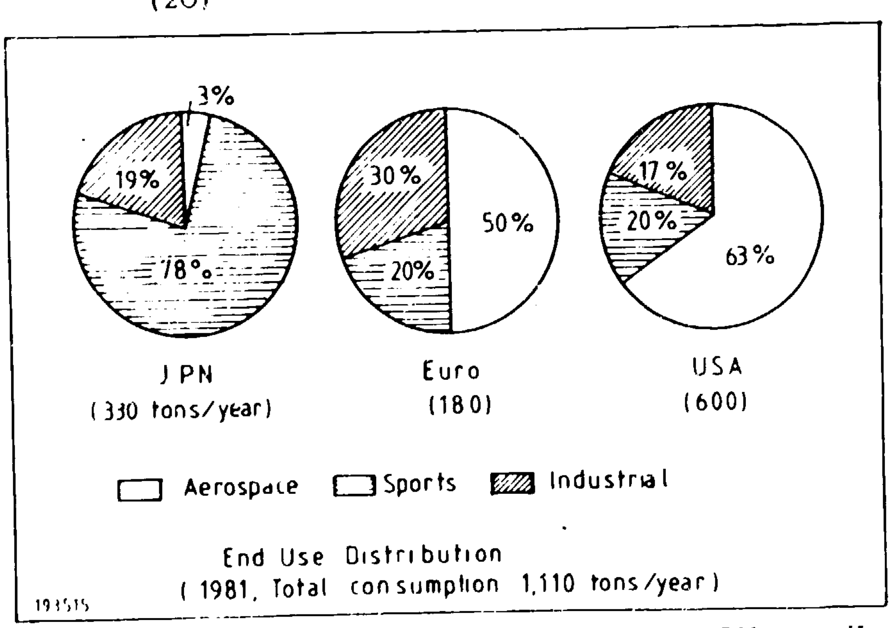


Fig. 27 End use distribution of carbon fibres (basis:1983 with total consumption of 1110 to) (20)

application, namely aerospace in Western countries and sporting goods in Japan, which again are exported all over the world. With lower carbon fibre price and increasing development of process technology for composites, the growing demand will be directed mainly to the field of general industrial application.

The following contributions during this Seminar will discuss in more detail the various fields of application. Only a brief survey can be given in this introductory paper.

4.1. Application in aerospace

Light weight structures are preferentially needed in aerospace applications. The US space shuttle (Fig. 28) (21) for instance consists in main parts of carbon fibre reinforced epoxy resins (cargo bay doors and booster rocket casings). But also modern commercial aircrafts use increasing amounts of carbon fibre reinforced composites instead of aluminium. Fig. 29 shows the progress of this development in EMBREAR (22) Fig. 30 (23) gives a forecast of probable replacement of conventional metals by advanced composites in commercial aircraft until year 2000.

There are already airplanes in development whose whole structure consists of composites instead of metals. Also in inner parts of airplanes metals are replaced by advanced composites, for instance the columns supporting the floor panels or the seats for the passengers. (see Fig.31) (24).

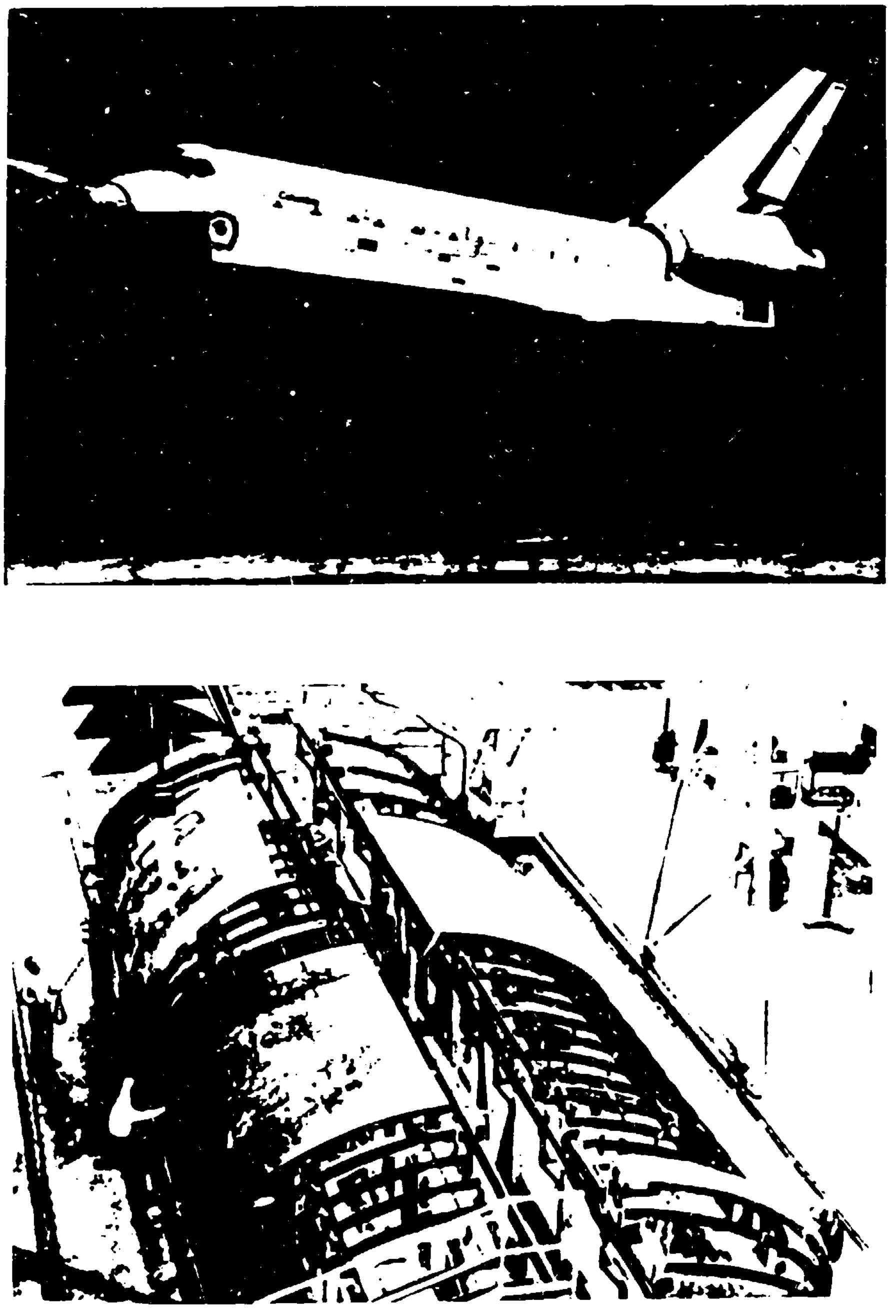


Fig. 28 Doors of the load room of the US space shuttle in construction at Rocketyne International (21)

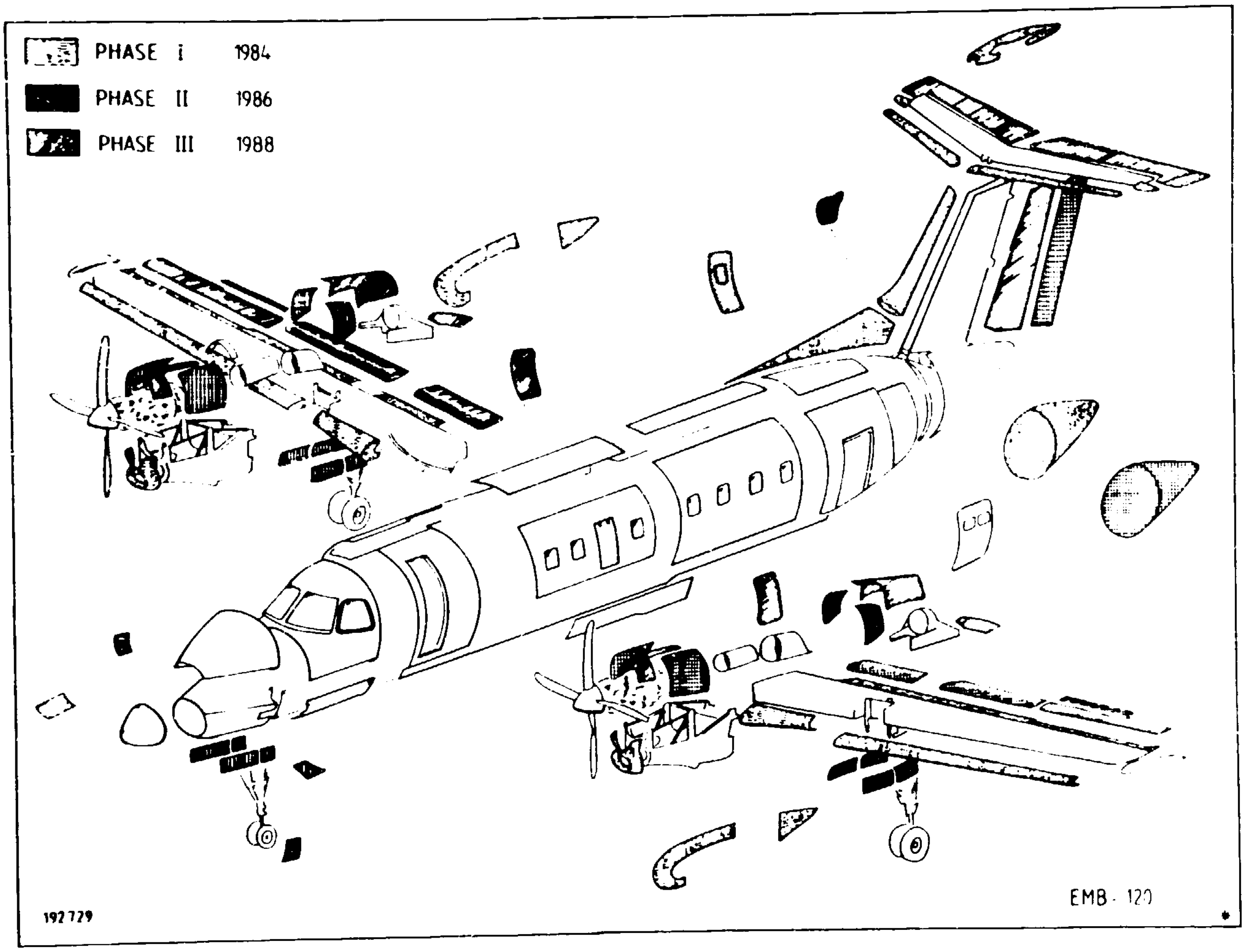
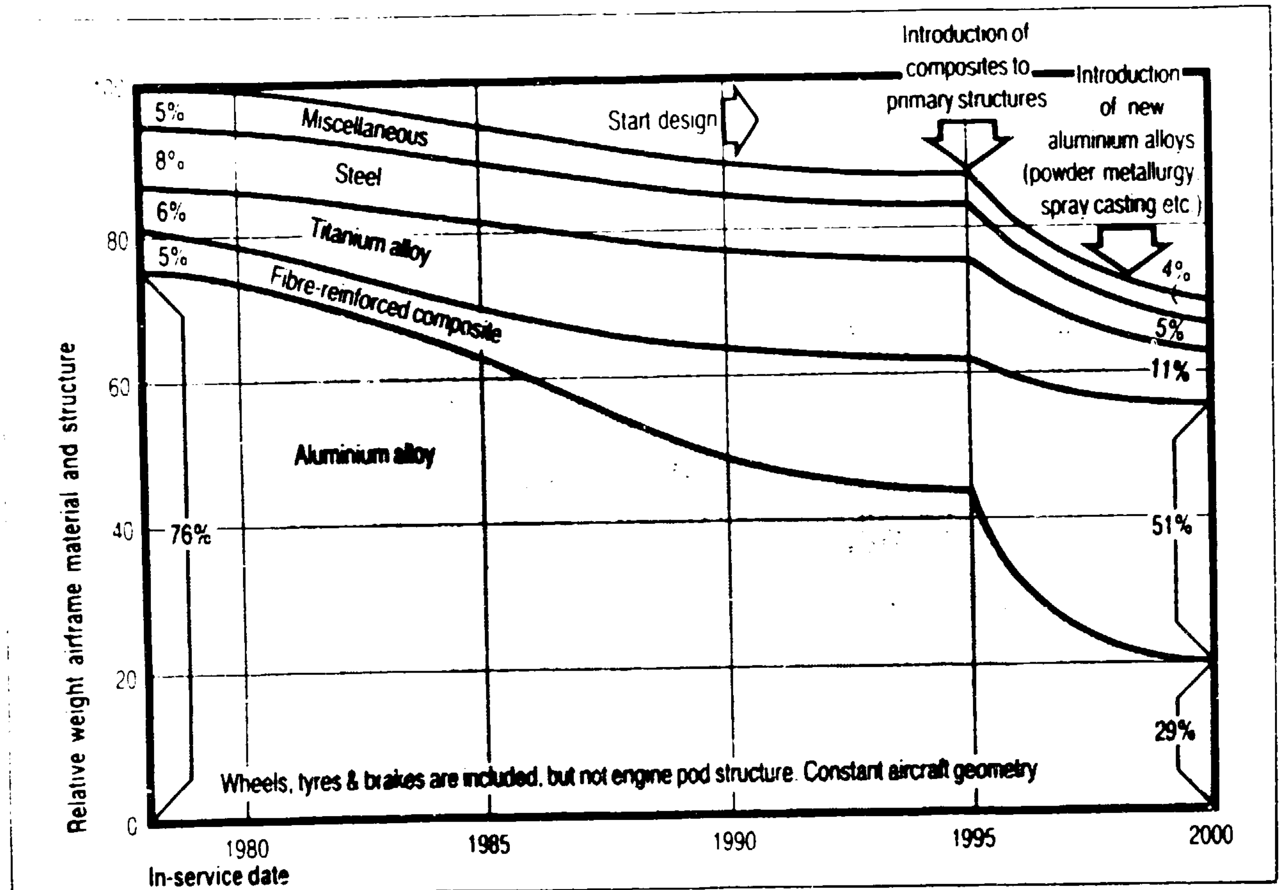


Fig. 29 Structural parts in EMBREAR's Comuter plane, Brazil (22)



By the year 2000 AD the amount of fibre-reinforced composite in use in civil planes will rise dramatically in response to rising energy costs

Fig. 30 Forecast for materials in commercial aircrafsts industry until year 2000 (23)

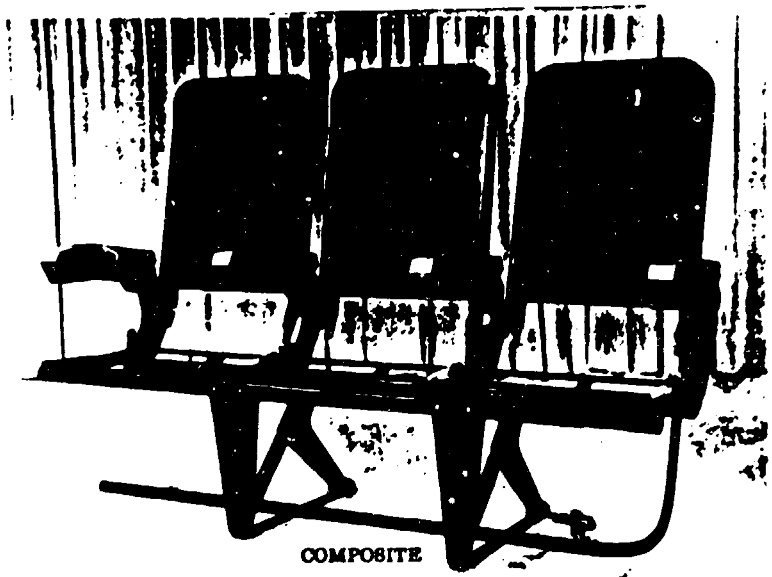


Fig. 31 Seats in airplane made from carbon fibre reinforced composites (24)

4.2. Application in transportation

Because of the requirements for the replacement of metals in primary structures of airplanes and based on the years long critical tests, the quality of carbon fibre reinforced composites andtheir processing technology have been largely improved. Car industry can take advantages in using this experiences for replacement of various metal parts in the cars. It seems today, that parts of the outer structure will be fabricated by glass fibre reinforced composites mostly. Highest chances for advanced composites are given at the moment to leaf springs, driveshafts, parts of frames and others where higher stiffness is needed. Fig. 32 (25) shows parts of a frame of a car. In racing cars, such structural elements are already in practical application.

One can assume, that all leading automobile companies are mostly interested to use advanced composites as part of the engines. The communication on this subject, however, is very restricted because of commercial secrets.

A further new development for transportation purposes, a transportable bridge with 40 m length must be mentioned. It has been designed for vehicles up to 66 t weights (26). All loadcarring structural elements were made from unidirectionally carbon fibre reinforced epoxy, thus achieving a meter weight of the bridge of only 500 kg (see Fig. 33).

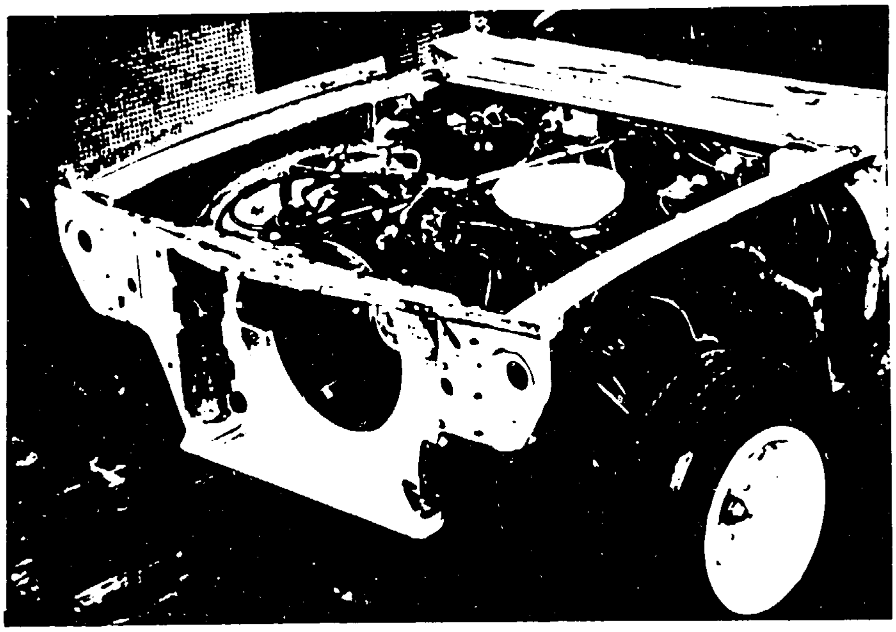


Fig. 32 Frame of a FORD model car made from advanced composites (25)

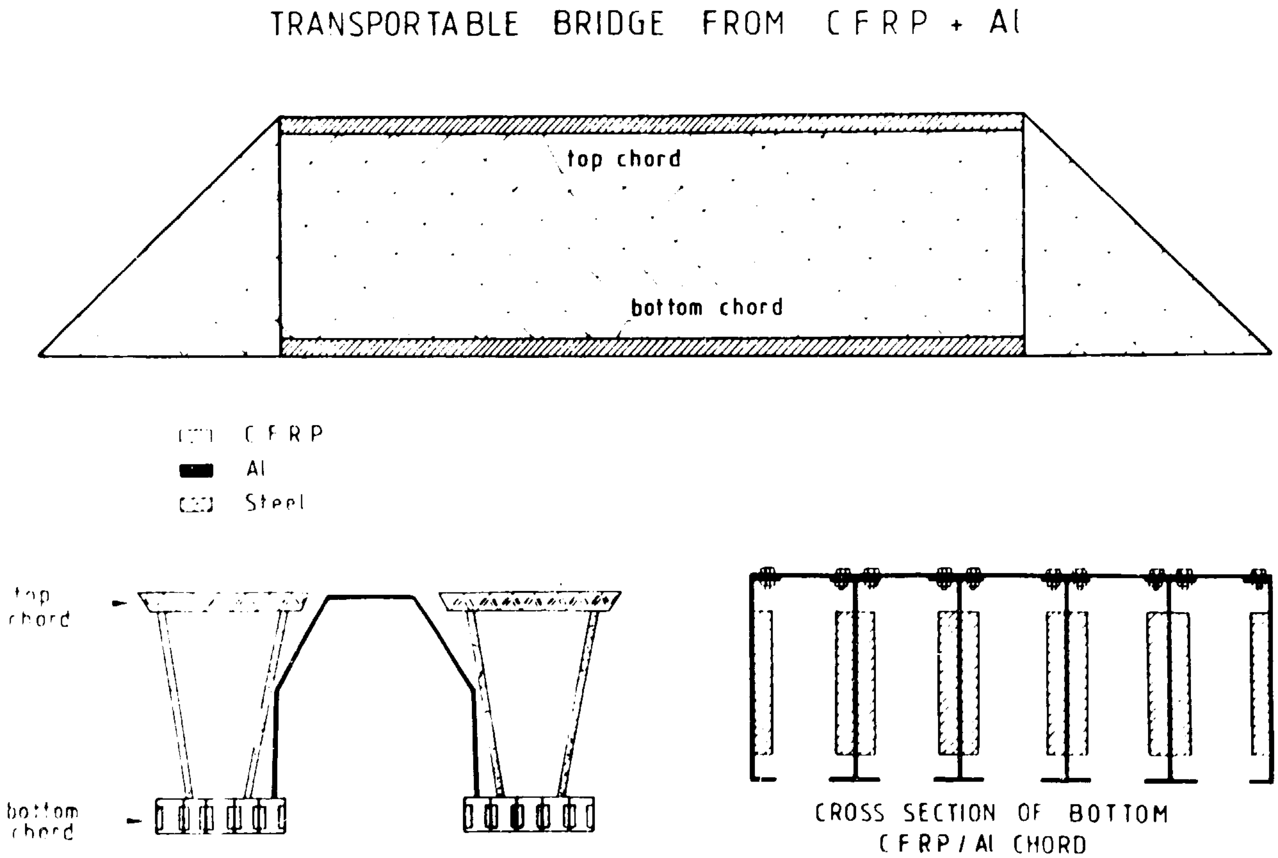


Fig. 33 Transportable bridge with loadcarrying structural elements of carbon fibre reinforced composites, made by pulltrusion (26)

4.3. Application in machinery and apparatus

The successful applications for turbine blades, compressor blades, windmill blades, ultra centrifuges, fly-wheels and in other machinery is not refered here because of the following main lectures given by the other experts. Only one interesting new application for structural elements with large size should be mentioned: these are light weight outer tubes for off-shore oil drilling equipments as shown in Fig. 34 (27). In this case, especially the high corrosion resistance of such advanced composites is needed. First in field application will be tested by ELF in cooperation with Aerospaciale in France end of this year.

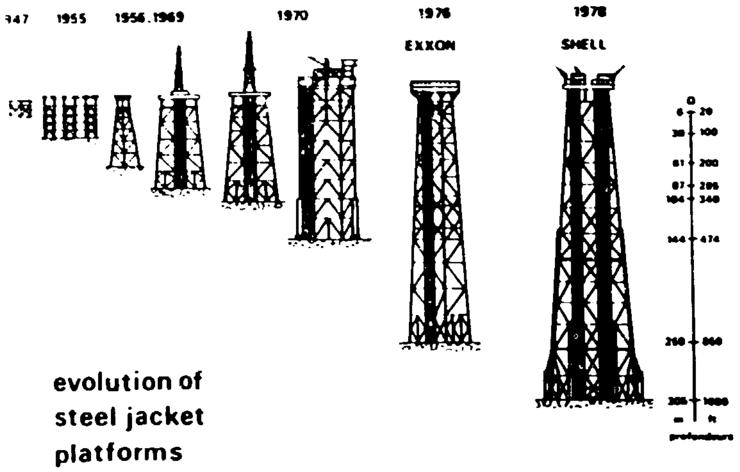
4.4. Cryogenic application

Materials for cryogenic temperatures require some other combinations of properties than for conventional temperatures. Especially the disadvantageous embrittlement of metallic materials at low temperatures is mentioned. Carbon fibre reinforced composites are most suitable for application at cryogenic conditions because:

1. the room temperature strength properties remain unchanged, even at lowest temperatures.
2. The interlaminar shear strength in polymer matrix composites improves with lowering of the temperature. Fig. 35 (28) represents own measuring results.
3. Carbon fibres have a good thermal and electrical conductivity. Surprisingly, these transport properties do nearly disappear at lowest temperatures, because of the contribution by electrons is completely eliminated. This behaviour is shown in Fig. 36 (29).

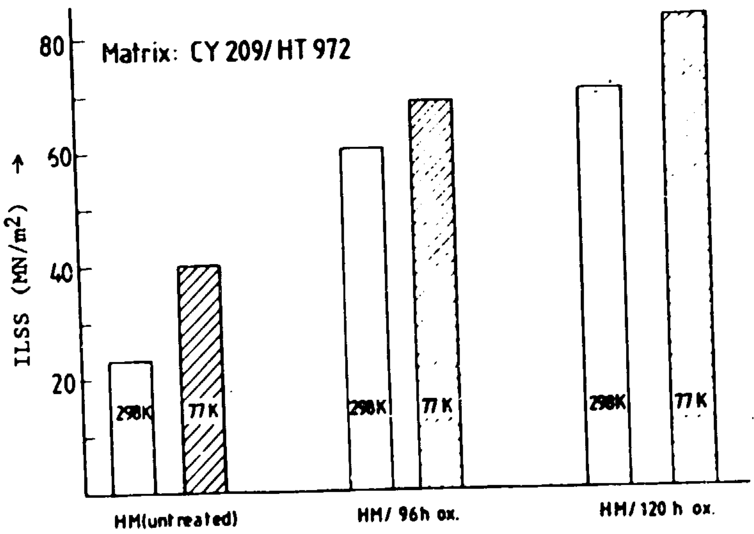
COMPOSITE TUBES/STEEL TUBES COMPARISON

(4"1/2 SATELLITE TUBES)



	STEEL	GLASS	CARBON
OUTSIDE DIAMETER (MM) .	114.3	118	118
TOTAL THICKNESS (MM) ..	7.4	7.3	7.3
SPECIFIC GRAVITY OF MATERIALS	7.8	2.1	1.55
LINEAR WEIGHT IN AIR (KG/M)	19.6	6.6	5.1
LINEAR WEIGHT IN WATER (KG/M)	17.0	4.7	3.3

Fig. 34 Application of carbon fibre reinforced tubes in off shore drilling . The light weight of carbon fibre reinforced composites becomes most important with increasing drilling depth (27)



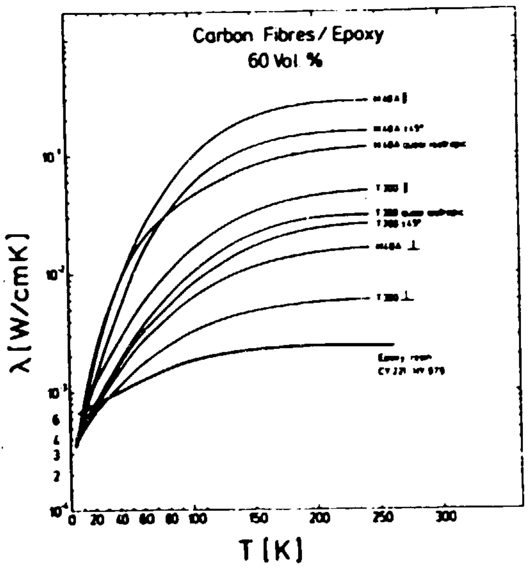


Fig. 35 Increase of interlaminar shear strength of fibre reinforced composites if measured at cryogenic temperatures (28)

Fig. 36 Thermal conductivity of carbon fibres in comparison with polymers at lowest cryogenic temperatures (29)

These properties offer promising applications in pulsed superconductive electromagnets.

Fig.37a and b (30) give some information on a joint European TORUS project for fusion experiments. The disadvantage of application of steel as material for the support in such a torus is the high lost by eddy currence, as well as the low resistance against fatigue and the high thermal conductivity of steel. Carbon fibre reinforced polymers offer an advantageous solution.

Finally, carbon fibres as substrat for superconducting niobium carbonitride layers are in development for this special application(31).

4.5. Medical application

Alsothis chapter will be treated in a main lecture. We have two groups which have to be considered, firstly the application in apparatus, and secondly, the application as implantation material. In the first group, Fig. 38 (32) shows a brand new application, namely a chair made from carbon fibres with the enormeous advantages of the low weight. May I draw your attention to the second group especially. Fig. 39 (33) shows a successful application of carbon fibres as ligament replacement at the human knee. These operations are performed successfully with hundreds of patients in Germany already. Fig. 40 (34) shows a human hip joint replacement. This application is supported in Germany by years long Governmental program. It is hoped that this application will be realized in the nearest future.

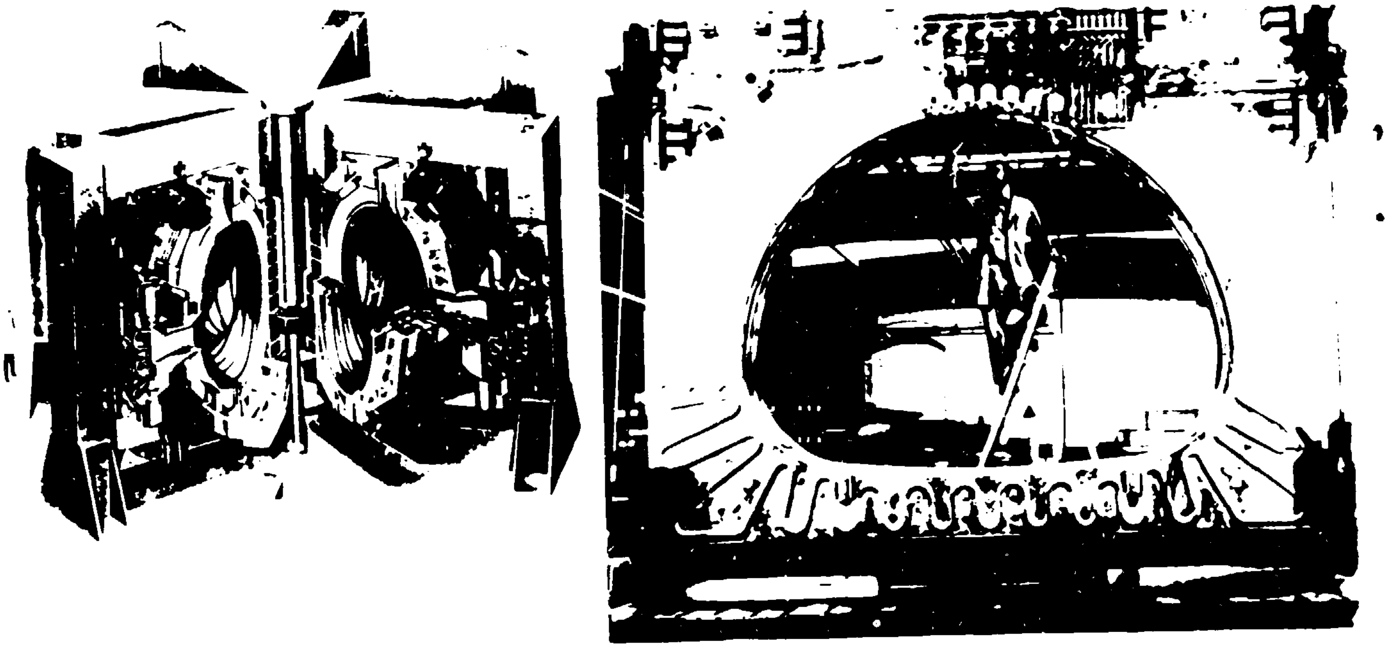


Fig. 37 Torus for pulsed superconductive electromagnets in the joint European torus project (30)

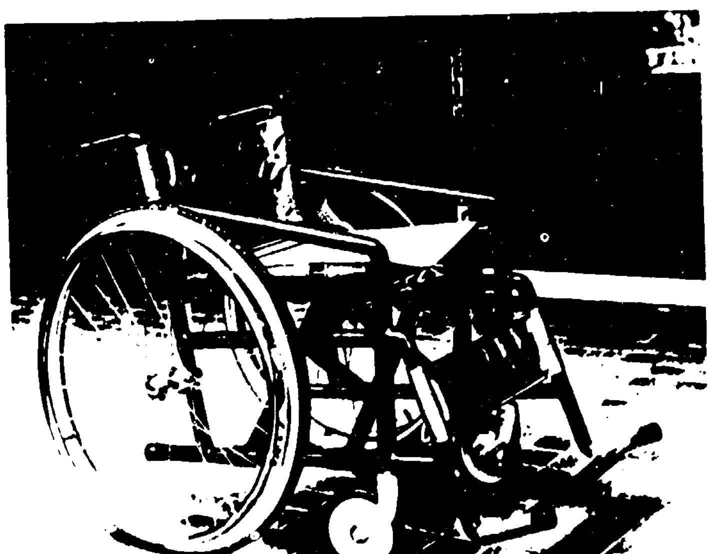


Fig. 38 Light weight transport chair, made from carbon fibre reinforced composites (32)

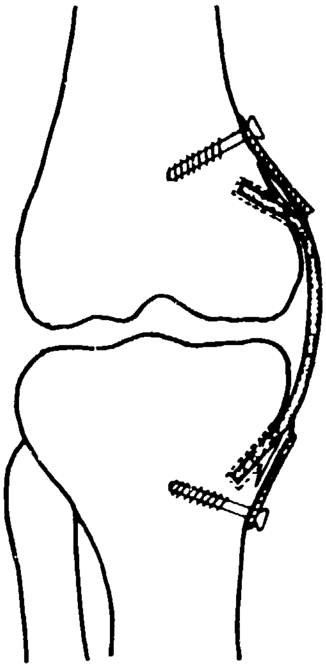


Fig. 39 Replacement of ligaments by carbon fibres (33)

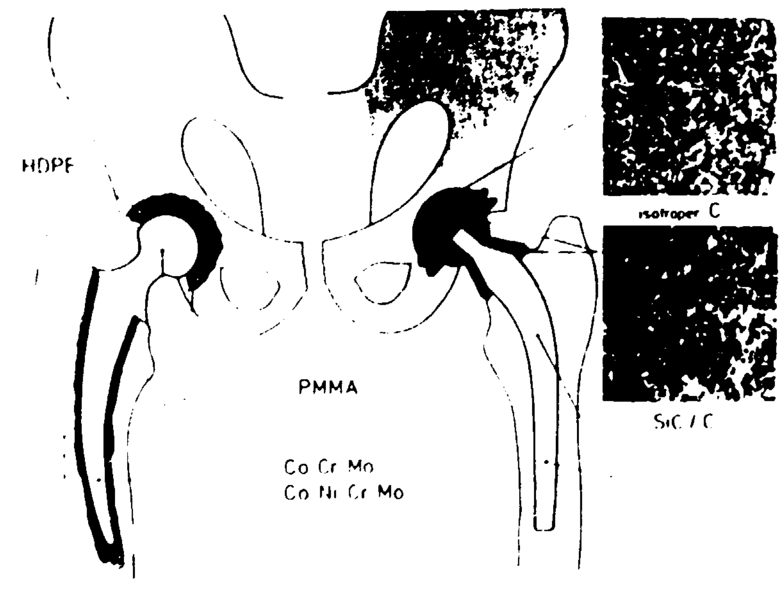


Fig. 40 Carbon fibre reinforced inplantation material for hip joints (34)

5. Final Conclusions

We can conclude: Carbon fibres as the backbone of new revolutionary materials are available today in high performance quality. The prices have been reduced drastically already and will be reduced even more in future by large scale production and additionally by using heavy tow PAN as precursor and large scale application of carbon fibres in form of multifilament tow.

Considerably high costs of today's high performance advanced composites with low filament tows are caused by the process technology, which uses prepreg/autoclave curing techniques. For broader application these techniques for manufacturing of composites must be simplified such as by sheet molding, pulltrusion or similar techniques. Especially thermoplastics as matrix offer a new economic way to use this miracle material "carbon fibre".

It is understandable, that also in composites with thermoplastics the design engineers want to apply the outstanding carbon fibres in combination with an outstanding polymer and for most critical application already.

This is the same situation again as it has been always with C-fibres in epoxy for aerospace, namely beginning with an extraordinary application. Engineers ask therefore at first for thermoplastic polymers which have highest thermal resistance and complete corrosion resistance. Even the poly-sulfones, which were candidate materials as heat resistant matrix for carbon fibre reinforced composites during last years have not brought the expected break-through because they have not proved to be resistant enough against solvents and oils.

A new thermoplastic matrix material, the so-called PEEK, a polyether ether ketone developed by ICI is now in discussion. Carbon fibres combined with this matrix promis a candidate future material, if the process difficulties with this high melting polymer can be overcome, and if the high costs for this special polymer can be justified by outstanding properties of the composite.

One should not forget, however, that carbon fibres, if they are available at low prices - even if they have outstanding properties- could be applied also in conventional low price thermoplastic polymers for broadest applications.

As general conclusion, one can state that there remains much development work to be done for chemists, materials scientists and engineers to start a new material age with this revolutionary material "carbon fibre".