Journal of Applied Sciences Research, 9(8): 4921-4926, 2013
ISSN 1819-544X
This is a refereed journal and all articles are professionally screened and reviewed

ORIGINAL ARTICLES

Some Structure-Properties Relationships of Carbon fibres (Review Article)

A. Bendak

National Research Centre, Textile Research Division, Cairo, Egypt

ABSTRACT

A reviewed study of the influences of carbon fibres structures on the acquired properties are thoroughly investigated. Structural influences are adopted via some important mechanical, thermal and electric properties. Skin-core texture of carbon fibres reveal some optical activity which arises from preferred orientation in the fibre structure.Tensile strength and tensile failure can be acquired from the perfect quality control of carbon fibre production. Carbon fibre is considered as linear elastic. The compressive fracture changes from a shear to a microbuckling mode with increasing the fibre anisotropy.The relation between the thermal expansion and Young's modulus of carbon fibre as well as electric properties are ascribed to the changes in its fine structure. The property structure relationship depends on the perfection, orientation and size of crystallites.

Key words: Carbon fibre, structure, texture, tensile strength, tensile failure, elasticity, compressive strength, thermal and electric properties.

Introduction

Modern Carbon fibre (CF) is developed upon polyacrylonitrile fibre (PAN) pyrolysis. PAN fibre is converted into CF by treating PAN-precursor in an oxidizing atmosphere at high temperature. The oxidized fibre is carbonized at temperatures above 1000^{o}C to produce CF. CF and its composites find a wide application in high-technologies. CF has been industrially prepared from PAN and pitches. PAN affords CF with excellent mechanical properties. Pitches afford CF with high modulus and relatively low strength potentially at a low cost (Bahl, *et al.,* 1981; Yamane *et al.,* 1987; Donnet and Guilpain, 1991; Ismail, 1991; He and Li, 2007; Sedghi *et al.,* 2008).

The physical adsorption characteristics of CF have permitted some developments of a number of new applications such as antibacterial wound dressing , disposable gas masks and polarizable electrodes as well as the use of activated CF in adsorption separation and catalysis applications. In all cases the activated CF can provide higher efficiencies (Wu *et al.,* 2007; Zhan, 2007; Luo, 2007; Shan, 2007; Jain *et al.,* 2009). CF is being utilized in increasing quantities in the aerospace industry because of its high strength, high modulus and low density. There are potential applications due to its electrical resistivity. The application can be increased upon further lowering the fibre resistivity (Wesson and Allbed, 1990). PAN-based CF has wide uses due to its high strength and relatively low cost. Mesophase (MP)-based CF has developed for stiffness critical uses. It has very high elastic modulus, its strength is lower than PAN-based CF and its cost is much higher. Another type of CF is grown from the chemical vapour deposition and subsequent pyrolysis of the hydrocarbon-hydrogen mixture. The resulted fibre has very high electrical and thermal conductivity (Zhang and Shen, 2008).

Structural Influences:

Drawing step in fibre processing reduces the denier of the filament and increases the molecular orientation to yield tensile property. Thus production of high modulus CF from any given precursor, necessitates high preferred orientation of the filament in a direction parallel to the fibre axis (Wesson and Allbed, 1990). Young's modulus depends on two factors (i) degree of orientation and (ii) degree of perfection (Ehrburger *et al.,* 1978). The tensile strength and orientation in PAN precursor increase with the stretch ratio during spinning (Fitzer *et al.,* 1979a; Khan *et al.,* 1991; Khan *et al.,* 1999). If the fibres are retrained during the early stages of pyrolysis, the length shrinkage as well as the loss of preferred orientation occur (Ohima *et al.,* 1983). A marked improvement can be noticed in orientation during carbonization with increase of the heat treatment (Lewin and preston, 1985). The carbonization of the amorphous PAN precursor results in a decrease of the average orientation of the given CF (Tsai and Lin, 1990).

Corresponding Author: Ahmed El Bendak, National Research Centre, Textile Research Division Cairo, Egypt
E-mail:- an_elbendak@hotmail.com

Oxidation of PAN is one of the important steps in the development of CF of best mechanical properties. Oxidation step is carried out to such an extent that about 50% cyclization takes place. The CF possesses high tensile strength. PAN structure is cyclized by increasing the residence time and the excess oxygen-containing groups are subsequently reduced by treatment with solution of pyrogallol (Mathur *et al.,* 1988). The tensile strength of CF is found to be 25% better than that obtained by conventional method (Bahl *et al.,* 1979; Tsai and Hualin, 1991). The degree of cyclization of oxidized PAN-based fibres is determined by shrinkage during oxidation. Thus 24% shrinkage corresponds to 50% cyclization (Bahl *et al.,* 1984). The degree of cyclization of PAN-based CF is of importance for the control of CF properties (Tsai and Lin, 1991a).

A structural differentiation can be made between PAN fibres thermally treated in the temperature range 1000^{o}-1500^{o}C, to be named carbon fibres, and PAN thermally -treated above 2000^{o}C, named graphite fibres. The structural units of carbon fibres consists of turbostratic layers which can split, fold to join other basic structural units forming microdomains. The fine structure of carbon fibres is not a homogeneous monolithic carbon unit but a chaotic collection of structural units formed into microdomains with some pores. The basic units and some of the microdomains are established during the formation process of the fibres.

The PAN fibres prior to carbonization exhibit some structural levels. The same organized levels can be applied to carbon fibre types:

- molecules are stacked together creating small coherent domains (basic structural units). At the next stage of organization, a microstructure is developed (~100nm) can be defined by microdomains consisting of assemblies of molecules with long orientation order. These are elongated along the fibre axis. They are limited laterally by pores. The characterization of the basic structural units as well as the micro texture can be determined by combining together the wide-angle x-ray scattering (WAXS), the small-angle x-ray scattering (SAXS), selected area diffraction (SAD), transmission electron microscopy (TEM), bright field (BF), and dark field (DF) imaging in the TEM. The highest level of organization defines the texture of the fibres, reflecting the statistical orientation changes of the molecules at very long range. The fibre texture can be readily observed in the SEM and can be deduced from optical microscopical studies (Shioya and Takaku, 1989; Takaku and Shioya, 1990).

The basic structural units are built up through several stages during the conversion of the fibres from the stabilized state to graphitic stage. At low temperature after stabilization, the oriented structural units are isolated at temperatures where the heteroatoms are being eliminated; pores are being formed owing to elimination of heteroatoms and increased densification. At higher temperatures, disordered layers may appear. At extremely higher temperature, planar layers of graphitic nature starts to appear. The changes in perfection and ordering of CF are apparent in high resolution electron micrographic studies. Coagulation of the polymeric PAN fibres gives rise to enlarged microfibrils separated by large pores. The uncollapsed fibres are removed from the spinning bath, washed , quenched, freezed, dried to prevent structure collapsing during drying step. A change in density of PAN material is apparent from the exterior toward the filament interior during the fibre formation. The microfilaments collapse to form a coherent mass, is still retaining its identity. The origin of microfilaments differs from rayon to PAN formed by coagulation process. The structure and orientation that control the final properties of carbon fibres derived from rayon or PAN can be readily distinguished.

CF layers:

Carbon fibres based on PAN precursor show some microdomains in a three dimensional structure is thoroughly given (Takaku *et al.,* 1985; Bendak, 2003). The microdomains near the fibre surface are highly oriented relative to those in the fibre interior. This may be due to the coagulation conditions during fibre spinning and then a complicated phenomenon is developed. Some pores exist in the fibre formed by gradual densification of the carbonized material during thermal treatment. In high-strength carbon fibres based on PAN precursor, the pores provide initially channels for removal of volatiles formed during the pyrolysis stage. PAN-based CF open pores transform into closed ones at about 1100^{o}C (Takaku *et al.,* 1985). This is based on the measurement of the fibre density and the fibre diameter remains unchanged for thermal treatment up to about $2000^{o}C^{.}$ The density is furtherly increased above 2000^{o}C and the fibre diameter decreases. The structural units form large layers, can split into smaller ones or can bind with other layers. The bonding forms cross-linking, tetrahedral bonds giving rise to lateral cohesion in the fibre skeleton (ASTM, 1981). The irregular collection of structural units become perfect in alignement and orientation. The variation in perfection tendency of the structural layers from the high strength CF (treated at about 1500^{o}C) to the high modulus PAN-based CF (treated at above 2000^{o}C) is consisted with carbon fibres from various precursors (Wang *et al.,* 2008a; Jain *et al.,* 2009).

Core texture of CF:

CF can exhibit a skin-core texture, is a result of high preferred orientation in the skin area by a higher density of material near the surface of the filament, or by oxidation gradient between the outer and inner parts formed during the stage of stabilization. The optical activity of the material arises from the preferred orientation (Mathur *et al.,* 1986). It can be observed that there is a modulus gradient as well as a thermal expansion coefficient between the skin and the core within the carbon micro-fibre (Ehrburger, 1990b).

Mechanical Properties:

i) Tensile strength:

The tensile strength of CF is determined on the single filament test (ASTM, 1989) as well as by the strand test. In the first one, the mono filament is separated from CF tow, mounted carefully to ensure axial alignment with the tensile direction. The filament test is very intensive requires statistical determination. The strand test is more rapid and accurate enough. The CF tow is impregnated in an epoxy resin to have a rigid sample capable of sustaining a uniform load on the individual filaments. The elongation at break of the cured resin must be significantly larger than that of the CF (ASTM, 1981).

ii) Tensile failure:

Improving the tensile strength of CF can be acquired from the perfect quality control of CF production. This can be achieved by reducing the particulate materials as well as reducing the created bubbles during gas evolution. The broken CF based on PAN precursor, fractured in glycerol medium are examined by TEM and SEM (Wesson and Allbed, 1990). The internal and surface flaws that initiated failure show evidence of mis-oriented crystallites. Internal flaws which do not initiate failure when the walls containing crystallites oriented towards the fibre axis. The presence of mis-oriented crystals initiate failure and not flaws. The mechanism of failure is given elsewhere (Fitzer *et al.,* 1979a).

Most of the research on the bromination of MP-pitch precursor for CF reveals minimum effects on its mechanical properties, while the oxidation resistance is enhanced (Bahl, *et al.,* 1981; Yamane *et al.,* 1987). The electrical resistivity decreases (Fitzer *et al.,* 1979b; Nardin *et al.,* 1990). This responds good in CF application in electromagnetic interference shelding. The effect of bromination on electrical resistivity is less pronounced in MP-pitch precursor CF. This effect is related to the less graphitic nature as indicated by the lower tensile modulus. This suggests that bromination induces flaws in CF (Fitzer *et al.,* 1979a; Fitzer *et al.,* 1979b). The tensile strength of CF based on PAN precursor is greater than that of the CF based on MP-pitch precursor. The MP-based CF with high strength has more turbostratic structure than the ultra-high modulus CF. The fine structure of the strong CF based on the MP precursor is nearly similar to that of high modulus CF based on PAN precursor. The folded structure is suggested to be a result of lower graphitization ability (Fitzer *et al.,* 1979). One of the outstanding properties of CF and carbon/carbon composites is that the tensile strength does not decrease with increasing the temperature.

iii) Elasticity:

CF is considered to be linear elastic because of the apparent linear stress-strain plot at the usual rates of elongation. It was indicated that a non-linear behaviour, namely the increase in ultrasonically measured modulus with increasing load (Nardin *et al.,* 1990), an increase in the dynamic modulus is shown with increase static strain (Voet, 1975). The increase in torsional modulus with increase in tensile stress and a decrease in Young's modulus with increased bending strain are also indicated (Jones and Duncan, 1974).

The increase of modulus with increasing the strain can be interpreted in terms of gradual straightening of the crystalline regions along the fibre axis. This is consistent with the correlation between the preferred orientation and Young's modulus for rayon based CF precursor (Mathur *et al.,* 1986). Worthy to mention that Young's modulus of PAN-precursor CF correlates well with its crystallite dimensions (Takaku et al., 1985). The shear modulus of grafitized CF can be expected to be lower than that of CF due to its nonplanar turbostratic layers. The shear CF based on rayon precursor as well as CF based on MP precursor are distinctly lower than that of CF based on PAN precursor. The scatter can be ascribed to the combination of crystals of various perfections in transition from the turbostratic to the graphitized structure. Electrochemical etching of CF can remove the enter layers in contrast of possible oxidation producing some pits. The increase in tensile strength of etched CF can be related to microvoids removal from CF at its outer layer. Etching process shows some increase in tensile strength as a decrease in the modulus as a function of weight loss due to etching CF. The shear modulus of CF from PAN precursor conforms with the variation of high-strength of MP-pitch type CF fibres treated at lower temperatures, exhibiting less perfection of its crystallites.

iv) Compressive strength:

Two major reasons are indicated to improve the compression strength are i) composites are subject to flex, which with low compressive strength requires thicker composite with an increase in weight to compensate and ii) submarines going very deep and retaining buoyancy for safety reasons, a fibre reinforced composite pressure is needed to reduce weight and having strength and reliability. The CF compressive fracture changes from a shear to a microbuckling mode with increase in anisotropy (Jones and Duncan, 1974). Thorough investigation of compressive strength CF/epoxy composites as a function of heating is given (Watanabe, 1993a), where a distinctive change from shear failure to microbuckling as the temperature approaches the glass transition temperature of the matrix (Wang *et al.*, 2008a). Failure of the composite is dependent, at low temperatures on the compressive strength which can be ascribed to the shear across both matrix and fibre. Recoil test reveals broken fragments, which appears in the SEM. A shear failure in high modulus MP-pitch based CF as well as a knik band in PAN-type precursor CF are observed. The failure of PAN-precursor CF is a result of initiation of cracks on the tensile of a bent fibre. This may propagate to a knik band on the compression side, forming a step in the route of cracks. This finding can be attributed to the effect of buckling instability combined with the high strain caused bending in recoiling taken place.

The presence of microfibrils is observed in SEM, following the compressive failure. Microfibrils can exist in CF based on PAN, rayon and MP-type precursors (Ehrberger, 1990b). The compressive strength of CF can be increased by i) increasing the tensile strength of CF based on PAN-precursor, ii) decreasing the tensile strength in MP-precursor type fibre, iii) decreasing the Young's modulus, iv) increasing the d-spacing, v) decreasing the crystal site, vi) increasing the microvoids.

It can be concluded that the fine structure controls the compressive failure of the CF. Implanting boron ions in MP-based CF results in lowering the perfection and size of crystallites (Hermans *et al.,* 1985). The torsional modulus of CF depends on the fine structure. The decreasing disorder in the crystallites structure lead to higher torsional effect. There is an effect of matrix modulus on the compressive strength as well as an effect of CF-matrix adhesion. When the adhesion is low, the filament delamination from the matrix and the fibre undergo column buckling. The CF undergoes microbucking at intermediate adhesion while at higher one, CF compressive failure occurs. The CF can be compressively loaded to its maximum capacity.

v) Thermal expansion:

The relation between the coefficient of thermal expansion(CTE) and Young's modulus of CF can be ascribed to that the properties are controlled by the fine structure of CF. The property-structure relationship depends on the perfection, orientation and size of crystallites.

vi) Electric properties:

Electric and thermal properties are dependent on the fine structure upon determining the electric resistance and thermal conductivity at normal temperature (Hermans *et al.,* 1985). The temperature-electric resistivity relationship of CF based on MP-precursor can be also adopted (Pan *et al.,* 1993a; Pan *et al.,* 1993b; Huang *et al.,* 2002).

V. Conclusion:

CF properties interpretation can be correlated with the fibres linear elastic property or the equality of tensile and compressive values. The assumption is valid at low strain and fails when the stress on the fibres approaches the yield or failure regions.

The tensile strength is limited by propagation of cracks in CF. It is expected that the tensile strength of CF based on MP-precursor exceeds that of CF based on PAN-precursor. The high strength depends on the extent of ordering crystal orientation whereas the high compressive strength depends on the high disordered behaviour.

CF is useful as space material and is characterized by minimization of thermal expansion coefficient and maximization of thermal conductivity. The material subjected to wide range variation in temperature favours property, while the latter is useful for maintaining the heat material balance.

References

ASTM D-4018-81, Tensile properties of continuous filament carbon and graphite yarns, strands, roving and toms.

ASTM Standards 133379-75 (approved 1989), Standards test method for tensile strength and Young’s modulus for high modulus single filament materials.

Bahl, O.P. and L.M. Mathur, 1979. Effect of load on the mechanical properties of carbon fibres from PAN precursor. Fibre Sci. & Technology, 12: 31-39.

Bahl, O.P., R.B. Mathur and K.D. Kundra, 1981. Structure of PAN fibres and its relationship of resulting carbon fibre properties. Fibre Sci. & Technology, 14: 147-151.

Bahl, O.P., R.B. Mathur and T.L. Dahmi, 1984. Effect of surface treatment on the mechanical properties of carbon fibres. Polym. Eng. & Sci., 24: 455-459.

Bendak, A., 2003. A review on Precursors for carbon fibre. Egypt. J. Text. Polym. Sci. Technol., 7: 1-20.

Donnet, J.B. and G. Guilpain, 1991. Structure characterization of carbon fibres. Composite, 22: 59-62.

Ehrburger, F., J.J. Herque and J.B. Donnet, 1978. Interface properties of carbon fibres composites. Proc. 5th Inter. carbon and graphite Conf. 1, London, pp: 398-404.

Ehrburger, P., 1990a. Surface properties of carbon fibres. Carbon fibres filament and composites, 147-161.

Ehrburger, P., 1990b. Protective Layers for special types of composites. Carbon fibres filament and composites, 327-336.

Fitzer, E. and R. Weiss, 1987. Effect of surface treatment and sizing of C-fibres on the mechanical properties of CFR thermosetting and thermoplastic polymers. Carbon, 25: 455-467.

Fitzer, E., K.H. Geigl and L.M. Manocha, 1978. Surface chemistry of carbon fibres and its influence on mechanical properties of phenolic based composites. 5th London Inter. carbon and graphite Conf., 1: 405-417.

Fitzer, E., K.H. Geigl and W. Huttner, 1979a. The influence of carbon fibre surface treatment on the mechanical properties of C/C- composites. 14th Biennial Conf. on carbon, The Pennsylvania State Univ., 236-237.

Fitzer, E., K.H. Geigl and W. Huttner, 1979b. The influence of carbon fibre surface treatment on the mechanical properties of carbon/carbon composites. Carbon, 18: 265-270.

Gshima, H., J.A. Woolland, A. Yavroulan and M.B. Dowell, 1985. Electrical and mechanical properties of copper chloride intercalated pitch-based carbon fibres. Synthetic metals, 5: 113-123.

He, F. and R.M. Li, 2007. Application of carbon fibre in defence and military. Gaokeji Xinnec Ya Yingyong 32:8-13; cf. Chem. Abstr., 2009, 151: 223199j.

Hermans, J., C.P.Jr. Beetz, I. Rahim and M.S. Dresselhaus, 1985. Proc. of the 19th Inter. Thermal Conductivity Conf., Yarborough, D.W., Ed., Plenum Press, 331.

Huang, J.M., C.H. Wang, 2002. Scanning force microscopy studies of the surface structure of activated carbon fabric. Text. Res. J., 72: 140-146.

Ismail, I.M.K., 1991. On the reactivity, structure and porosity of carbon fibres and fabrics. Carbon, 29: 777-792.

Jain, R., H.G. Chae and S. Kumar, 2009. Carbon nanofibre (CNE) reinforced PAN fibres. PMSE Preprints, 100, 453-454 cf. Chem. Abstr., 2009, 151: 427518x.

Jones, B.F. and R.G. Duncan, 1974. The effect of cooling on the mechanical properties of PAN-based carbon fibres. J. Mater. Sci. letters, 9: 162-164.

Khan, Z., Al-Sulaiman and J.K. Farooqi, 1999. Fatigue life predictions in woven carbon fabric/polyester composites. Advanced materials. Proc. of the 6th Inter. Symp. on advanced materials, Islamabad, Pakistan 7-18. Published by Khan, A.Q.Res. Labs, Kahuta, Pakistan.

Khan, Z.M., A. Ul Hag, N. Ahmed and A.Q. Khan, 1991.The drilling induced failure modes in high performance carbon fibre composite. Advanced materials 91:19-27. Published by Khan, A.Q.Res. Labs, Kahuta, Pakistan.

Lewin, M. and J. Preston, 1985. High Technology Fibres. Marcel Dekker Publ., N.Y. pp: 185.

Luo, Yi, F., 2007. Under innovating upon World' new high-Tech. fibres. Gaokeji Xianwei Yu Yingyong 32: 1-5; cf. Chem. Abstr. 2009,151: 223197g.

Mathur, R.B., O.P. Bahl, V.K. Matta and K.G. Nagpal, 1988. Modification of PAN precursors-its influence on the reaction kinetics. Carbon, 26: 295-301.

Mathur, R.B., T.L. Dhani and O.P. Bahl, 1986. Shrinkage behavior of modified PAN precursors-its influence on the properties of resulting carbon fibres. Polym. Degrad. and Stabil., 14: 179-187.

Nardin, M., H. Balard and E. Papirer, 1990. Surface characteristics of commercial carbon fibres determined by inverse gas chromatography. Carbon, 28: 43-48.

Pan, G., N. Muto and M. Miyayama, 1993b. Humidity sensitive electrical resistivity of carbon fibres. J. Mater. Sci. Letters, 12: 666-668.

Pan, G., N. Muto, M. Miyayama and H. Yanagida, 1993a. Microstucture effects on humidity sensitive electrical resistivity of carbon fibres. J. of Ceramic Soc. Japan, 101: 383-388.

Pennock, G.M. and E.O. Gara, 1990. Preparation of carbon fibre sections for light and transmission electron microscopy. J. of Mater. Sci. Letters, 9: 847-849.

Sedghi, A., R.E. Farsani and A. Shokuhfar, 2008.The effect of commercial PAN fibres characterizations on the produced carbon fibres properties. J. Mater. Processing Technology, 198: 60-67.

Shan, Q. and L. Qi, 2007. Development status and prospect of intelligent fibres and textiles. Xianwei Yu Yingyong, 2007, 32, 32-37; cf. Chem. Abstr. 2009,151: 223198h.

Shioya, M. and A. Takaku, 1989. Characterization of crystallites in carbon fibres by wide-angle x-ray diffraction, J. Appl. Cryst., 22: 222-230.

Takaku, A. and M. Shioya, 1990. X-ray measurements and the structure of PAN and pitch-based carbon fibres. J. Mater. Sci., 25: 4873-4879.

Takaku, A., T. Hashimoto and T. Miyoshi, 1985. Tensile properties of carbon fibres from acrylic fibres stabilized under isothermal conditions. J. Appl. Polym. Sci., 30: 1565-1571.

Tsai, J.S. and C. Hualin, 1991b. The effect of distribution of composite among chains on the properties of PAN precursor for carbon fibre. J. Mater. Sci., 26: 1996-2000.

Tsai, J.S. and C.H. Lin, 1990. The change of crystal orientation from PAN precursor to the resulting carbon fibre. J. Mater. Sci. letters, 9: 921-922.

Tsai, J.S. and C.H. Lin, 1991a. The effect of molecular weight on the cross section and properties of PAN precursor and resulting carbon fibre. J. Appl. Polym. Sci., 42: 3045-3050.

Voet, A., 1975. Dynamic mechanical properties and electrical resistance of carbon black. Interactions entre les elastomeres, 231: 247-252.

Wang, C., M. Jing, Y. Wang, Q. Wang, Y. Zhan, J. Wu, 2008a. Advances in carbonization and pyrolysis of PAN-based pre-oxidized fiber for C-fibres. Xiandai Huageng, 28:(7), 22-26, cf. Chem. Abstr., 151: 315-437.

Wang, W., P. Ciselli, E. Kuzenetsov, T. Paijs, A.H. Baber, 2008b. Effective reinforcement in C nanotube polymer composites. Phylosophical transactions of the Royal Soc. & Math., Phys. & Eng. Sci., 366: 1613-1626, cf. Chem. Abstr. 2009, 151: 427491h.

Watanabe, T., 1993a. Microstucture of carbon fibres. Bull. of Faculty Education (Yamaguchi Univ.) 43: 1-6.

Watanabe, T., 1993b. Biodegradation of pitch-based carbon fibre (graphite fibre)by microorganisms. Bull. of Faculty Education (Yamaguchi Univ.), 47: 1-7.

Wesson, S.P. and R. Allred, 1990. Acid-base properties of carbon and graphite fibre surface. J. Adhesion Sci. Technol., 4: 277-301.

Wu, Y.X., Z.S. Zhang, S. Zheng and B. Yu, 2007. Development situation analysis of domestic carbon fibre. Gaokeji Xianwei Yu Yingyong, 32 (2), 22-25; cf. Chem. Abstr. 2009, 151: 223195e.

Yamane, S., T. Biramatzu and T. Higuchi, 1987. Terayaka T1000 ultra- high strength carbon fibre and its composite properties. 32rd Inter. SAMPE Symp. 928-936.

Zhan, J.X., 2007. Civil aviation and advanced composite materials. Gaokeji Xianwei Yu Yingyong, 32, 6-10; cf. Chem. Abstr. 2009, 151, 223196f.

Zhang, F.F., T.N. Shen, 2008. Noteworthy technical problems of C-fifres in the large scale. Xianwei Yu Yingyong, 33, 1-4 cf. Chem. Abstr. 2009, 151, 315423p.