CHEMSYSTEMS
PERP PROGRAM

Carbon Fiber

PERP 2011S9

Report Abstract
May 2012

Nexant

Carbon Fiber

PERP 2011S9

May 2012

Alexander Coker,
Jun Goh and Kunal Patel

CHEMSYSTEMS
PERP PROGRAM

Nexant
www.chemsystems.com

Nexant's ChemSystems Process Evaluation/Research Planning (PERP) program is recognized globally as the industry standard source for information relevant to the chemical process and refining industries. PERP reports are available as a subscription program or on a report by report basis.

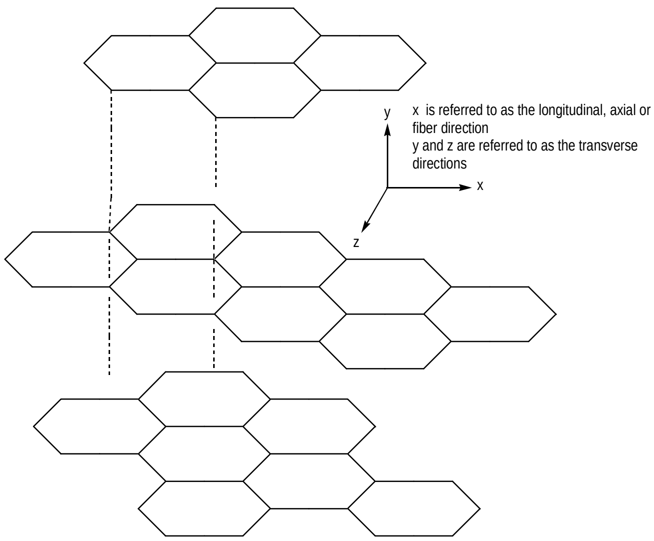
For further information about these reports contact:

Mrs. Heidi Junker Coleman, Global Support Manager, Multi-Client Programs: phone +1 914 609 0381 and e-mail hcoleman@nexant.com

INTRODUCTION

Carbon fiber is produced as thousands of individual solid filaments grouped together (and a bundle of such carbon fiber filaments grouped together is known as a tow). Individual filaments have diameters of 5-10 micrometers. Each filament is composed of ribbon-like crystals oriented more or less in the same direction (parallel to the long axis of the filament) interlaced with amorphous sections. Each crystal is composed of atoms that are 90 to 99+ percent carbon joined together in repeating hexagonal structures. The carbon fiber microstructure varies depending on the precursor it was made from and the processing conditions employed in its production. Carbon fibers have varying degrees of similarity to the structure of graphite depending on the extent of the crystalline component. A simplified illustration of the lattice structure of a carbon fiber (having high similarity to the graphite crystal lattice structure) is depicted below.

Figure 1 Carbon Fiber Structure



There is a small mis-alignment shown in the figure above which is meant to illustrate a turbostratic structure (parallel planes but misaligned). Depending on the precursor and processing employed, carbon fibers also have portions of their structure where the planes are not only turbostratic (mis-aligned) but also they are not even parallel but rather tilted/folded one on the other (i.e., amorphous).

The structure of carbon fiber results in a material with exceptionally high tensile strength and modulus of elasticity (stiffness) relative to its density. This high specific tensile strength and modulus, coupled with the relative chemical and biological inertness, high electrical/thermal conductivity, low coefficient of thermal expansion, exceptional fatigue and creep resistance, have led to ever increasing demand for the material. (The more highly ordered, parallel, and aligned are the planes, the more crystalline and graphene-like is the structure with attendant higher density and larger size of crystals. For a given precursor, the more the structure is like this (as a result of higher temperature treatment), the higher will be the tensile modulus, heat conductivity, and electrical conductivity, but - with all other things being equal (i.e., except the maximum pyrolysis temperature employed)– the lower will be the tensile, shear, and compressive strengths.)

Carbon fiber has a number of limiting factors that obviate its use in many applications on its own merits alone. Its shortcomings include that most of its properties are anisotropically derived (i.e., they are uniaxial - effective along one axis only), its compressive strength is only about half its tensile strength, it has relatively low shear and flexural strengths, low strain to failure, low toughness (although very resistant to failure, once it reaches the strain limit it breaks suddenly and catastrophically), it is unstable in oxygen environments above about 350 ^{o}C (at which point it starts to oxidize to carbon oxides), and it is unstable in oxidizing environments in the presence of alkaline media.

Therefore, for most commercial applications, carbon fiber is combined with other material(s) to form a composite. The other material(s) typically provide the matrix (or core) into which the carbon fiber is incorporated. Most often the key reason for the use of carbon fiber in most applications is to give structural reinforcement, and therefore these composites are called carbon fiber reinforced composites.

Major carbon fiber applications include:

- Aerospace and military (civilian aviation, military, and space)
- Consumer (sports and leisure, and other consumer goods)
- Industrial (wind turbine blades, ground transportation, pressure vessels, civil engineering, oil and gas, medical, and other industrial applications)

Nexant is cautiously optimistic about the future of carbon fiber. There is a strong sense that momentum is building and carbon fiber's long awaited growth potential may be on the verge of realization. Sustained demand and growing supply to meet that demand is promising.

The carbon fiber business is quite complicated and this is compounded by the fact that established technology holders guard their technology tightly. In this PERP report, Nexant has expended considerable effort to de-mystify the subject, and break it down into sections that facilitate structured comprehension. The report begins with a discussion of the carbon fiber value chain, structure, key properties, and classification. Following this, commercial production technologies and process economics for two standard grades of the material (i.e., high strength and high modulus) are discussed. An overview of the varied and myriad carbon fiber architectures and forms, as well as matrices and fabrication of composites is given. Finally, the wide range of commercial applications, and a breakdown of regional supply, demand, and trade, as well as demand by key applications is given.

TECHNOLOGY

Carbon fiber was first produced commercially using a rayon precursor.

However, today, carbon fiber production from polyacrylonitrile (PAN) precursor is by far the commercially dominant route employed, accounting for some 95-96 percent of global production in 2011. PAN precursor is produced from acrylonitrile monomer and a small quantity of typically two comonomers.

Pitch is also used to produce carbon fiber. Pitch is generally considered to be a mixture of hydrocarbons containing a large proportion of aromatic compounds. Commercially significant sources of pitch are petroleum pitch and coal tar pitch. Pitch based carbon fiber will probably still continue to have a niche demand for many years into the foreseeable future. This is due to the unique high-end properties that can be delivered by using mesophase pitch precursor (such as ultrahigh tensile modulus, and exceptionally high thermal and electrical conductivities) and the relatively cheap carbon fiber that can be delivered by using isotropic pitch precursor for low end (general purpose) applications.

Nexant does not believe there is any commercially significant production of carbon fiber from other precursor materials at the present time.

The key process steps in the production of carbon fiber, regardless of the precursor, generally include:

- Precursor production/preparation
- Spinning of the precursor into filaments
- Stabilization of the spun fiber
- Pyrolysis of the stabilized fiber
- Surface treatment to enhance its conversion to a composite
- Sizing (coating) to protect it during subsequent downstream handling.
- Filament winding

Recent developments have included improvement in carbon fiber equipment leading to increased productivity, higher online availability, and great energy efficiency (exemplified by Harper International). Research work has included developing cheaper feedstocks from which to produce carbon fiber, especially from renewable sources such as lignin (exemplified by Oak Ridge National Laboratory (ORNL) and Zoltek Industries), as well as the feasibility of using textile grade acrylic fiber (exemplified by Mitsubishi Rayon, ORNL/Fisipie and Zoltek/ Weyerhaeuser).

Commercial carbon fiber production from PAN and pitch are discussed in the report. An overview of the historical route from rayon is given, as well as a review of selected R&D work.

PROCESS ECONOMICS

Detailed cost of production estimates are presented for:

- Polyacrylonitrile (PAN) precursor via suspension polymerization with wet spinning
- High (3.5 GPa) tensile strength carbon fiber 12 K tow (230 GPa tensile modulus) from PAN precursor
- High (400 GPa) tensile modulus carbon fiber 4 K tow (2.1 GPa tensile strength) from pitch precursor

Detailed cost tables are presented on a USGC location, while summary tables are included for China, Japan, and N.W. Europe.

Detailed cost tables given in this report include a breakdown of the cost of production in terms of raw materials, utilities consumed (electrical energy, cooling water, fuel etc.), direct and allocated fixed costs, by unit consumption and per metric ton and annually, as well as contribution of depreciation to arrive at a cost estimate. Capital costs are broken down according to inside battery limits (ISBL), outside battery limits (OSBL), other project costs, and working capital. Major equipment items used in ISBL and OSBL is listed.

Summary tables give total project investment cost, working capital, net raw materials, total utilities, total direct fixed costs, total allocated fixed costs, and depreciation. Prices for the key raw materials, all utilities, and typical employee salaries are given in a separate pricing table (so that where desired more detailed cost tables can be constructed from the consumption factors in the detailed tables and the pricing table).

Sensitivity of carbon fiber production cost to carbon fiber plant scale is given. Variation of PAN-based carbon fiber production cost to PAN precursor cost and to PAN precursor plant scale is given.

A comparison of the relative merits, and advantages/disadvantages of the pitch process versus PAN process is given.

COMMERCIAL FIBER ARCHITECTURE

The carbon fiber form at the end of the carbon fiber production line is usually continuous filament tow. There is a wide range of architecture (unidirectional, two dimensional biaxials and triaxials, and three dimensional) and forms (fabrics such as weaves, knits, and braids, as well as multiaxials) that derive from continuous filament.

Figure 2 Plain Weave

Continuous filaments can also be cut into staple fibers, which can be milled into powder, needled into felts, chopped, formed into “tissue” or “paper” forms.

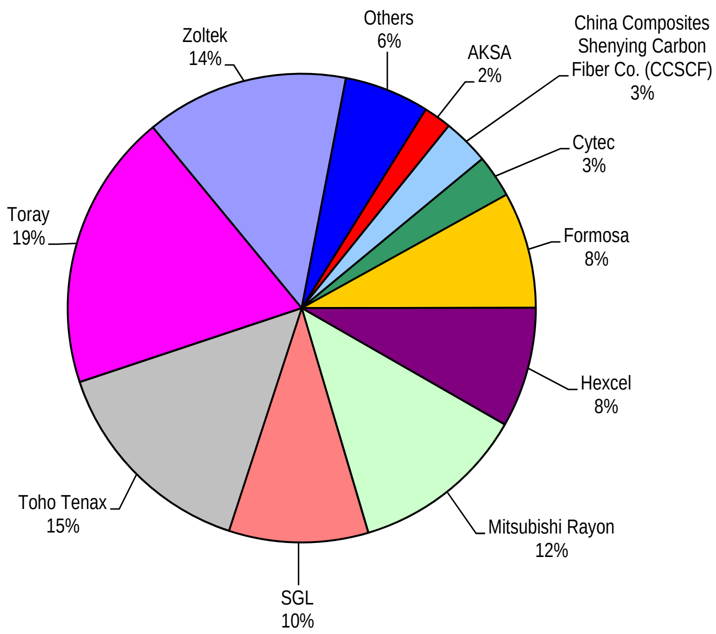
The primary material that is used to form a matrix for carbon fiber in the composite is polymer resins (thermosets such as epoxy, polyester, vinyl ester, phenolic thermosets etc., and thermoplastics such as PEEK); however, notable other materials that are used as matrices include amorphous carbon, metals, and ceramics.

Fabrication technologies range from contact molding lay-up to resin transfer molding to prepregs to filament winding and pultrusion. Downstream processing can cost up to three times the cost of making the carbon fiber raw material or in some cases even more (due to high requirement for skilled manual labor and lack of economy of scale).

COMMERCIAL MARKET REVIEW

The top four global producers in 2011 were Toray Industries, Toho Tenax (Teijin), Zoltek, and Mitsubishi Rayon, who collectively held around sixty percent of the worldwide nameplate carbon fiber production capacity.

Figure 3 Carbon Fiber Main Players

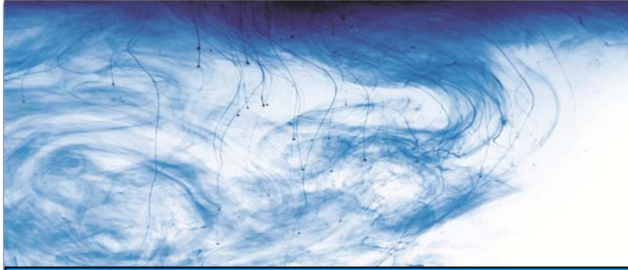


About one-third of the carbon fiber produced was large tow (i.e., > 24 K tow). By about 2016, Nexant expects that large tow will account for about half the carbon fiber produced; this is because the main drivers of future demand will be from the industrial segment (especially wind energy, automobile, pressure vessels, and the oil and gas sectors), a large proportion of which demand can be met by cheaper large tow carbon fiber.

The main consumers of carbon fiber in 2011 by tonnage were in the wind energy, aircraft, sports goods, and automobile industries. The main consumers in dollar terms were the aircraft, space, and military sectors.

- Global supply and demand data is given and discussed
- Global demand by application data is included
- Firm and speculative capacity additions to 2016 and 2021 is given
- Supply, demand and trade data is given and discussed for the regions of North America, Europe, Asia, and Rest of the World

- A list of plants in each of the regions above is given showing specific plant capacities, owning company, location, annual tonnage produced, and precursor employed



Nexant, Inc.

San Francisco
London
Tokyo
Bangkok
Bahrain
New York
Washington
Houston
Phoenix
Madison
Boulder
Dusseldorf
Beijing
Shanghai
Paris

www.chemsystems.com