"COMPOSITE" - THE MATERIAL OF THE FUTURE

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Abstract:

Composite have unique advantage over monolithic materials. Many of our modern technologies require materials with unusual combinations of properties that cannot be met by the conventional metal alloy. The recent trend of the composite materials in aerospace, space research, automobiles industry, atomic energy are very much interesting for researchers. C/C-SiC composites that incorporate hard particles like diamond, cubic BN and B_4C for cutting tools. SiC/SiC composites are being considered for advanced nuclear applications such as fusion blanket/first wall structures.

1. Introduction:

All advanced countries, is taking a big interest in composite materials, which many people see as 'the materials of the future'. The main concern is to get the costs down, so that composites can be used in products and applications, which at present do not justify the cost. At the same time researchers want to improve the performance of the composites, such as making them more resistant to impact. Many composite materials are composed of just two phases; one is termed as matrix, which is continuous and surrounds the other phases, often called the dispersed phase. Sometimes, because of chemical interactions or other processing effects, an additional phase, called interphase, exists between the reinforcement and the matrix. [1,6,9,10]

2. Recent trends in applications of ceramic and metal matrix composites:

Starting in the late 1970s applications of composites expanded widely to the aircraft, automotive, sporting goods, and biomedical industries. The 1980s marked a significant increase in high modulus fiber utilization. Now emphasis is being placed on development of newer metal/matrix and ceramic/matrix composites, as well as carbon/carbon composites, for high temperature applications. Applications abound, including underground pipes and containers, boats, ground vehicles, automotive components, sports equipment, biomedical products, and many other products design to have high medical performance and/or environmental stability coupled with low weight.[2,3]

For successful commercialization of composites, synthesis and fabrication methods must be economical and those based on infiltration show promise. M Cubed Technologies, Inc. (Newark, Delaware) has developed a cost-effective, pressure-less metal infiltration technique called PRIMEX for manufacturing large (0.5 m x 0.6 m x 0.75 m) complex ceramic-metal composite components including SiC/Al-Si, SiC/Si, B_4C/Si, SiC/Al, graphite/Si, graphite/Al-Si, and B_4C/Si/SiC. [5,7].

In this process, high strength preforms of ceramic particles/fibres are first produced, which allows machining of complex features before densification. A preform bonding technology has also been developed that can produce complex shapes such as beams, structures with cooling passages, and lightweight mirrors. After the preform is machined or bonded together, it is infiltrated with a molten metal. The reaction bonding that occurs during this process overcomes cost, shape and size limitations of mechanical fabrication approaches such as pressing.

Due to minimal shrinkage (less than 0.5%) in the final infiltration step, minimal final machining is required. The material composition can be varied to tailor such properties as thermal expansion, stiffness, manufacture mirrors for space and lithography applications. The infiltration technique has been scaled up for high volume manufacturing (10,000/month) of ceramic composite inserts for personnel armor using statistical process control and Kaizen techniques. [5]

Another chemical process developed and patented at Ohio State University is being commercialized by MetaMateria Partners (Columbus, Ohio) for making net shape carbide composites. In this process, called displacement compensation porosity (DCP), a low-melting (1200°C) metal alloy is pressure-less infiltrated into a porous carbide perform. An internal reaction produces a carbide phase that fills the pores, resulting in a dense net-shaped composite. By controlling the porosity, the metal content can be adjusted. Tailoring of microstructures is also possible.

With funding from the U. S. Air Force, MetaMateria is developing this process for making W/ZrC rocket nozzle inserts. ZrC is attractive because it has 1/3 the density of W, has a similar expansion, good thermal conductivity, hardness, and creep-resistance, and becomes ductile at 400°C. WC powder is first mixed with a binder and formed into a porous shape. After the binder is burned out, Zr_2Cu liquid (which melts at 1025°C) infiltrates the preform pores. A rapid reaction produces a fully dense material at 1200°C, which consists of W particles completely encapsulated by ZrC. Because copper forms on the surface, a washing with acid is required. This composite can be used above 2500°C and has a flexural strength of 684 MPa at 600°C. Wear applications based on carbide, nitride, and boride composites will also be developed in the future, as well as aluminide/ oxide composites.[5]

Germany's University of Erlangen-Nuremberg is also using a pressureless melt infiltration technique to fabricate multi-layer AlN/ AlSi composites. Si_3N_4 tape of 100 microns in thickness and aluminum foil are alternately stacked to form multi-layer packages and then heated in an inert gas atmosphere to 1000°C. Presintering of the tapes is not required.

The reaction involves a solution-precipitation process, where Si_3N_4 dissolves in the Al melt above 670°C followed by the precipitation of AlN. Excess aluminum is required for the metal layer. After reaction the composites consist of AlN layers, with a thickness of 300 mm containing Si precipitation and an Al-Si intermetallic layer. The thickness of this layer can be varied by changing the Si_3N_4/Al layer thickness.

These composites have a modulus of rupture above 200 MPa and a fracture toughness of 4.1 MPa-$m^{1/2}$. Potential applications include substrates, laminates, and heat exchangers. The process is economical and produces near net shapes. Joining and machining of parts is also easy to achieve.

The University is also developing lightweight magnesium alloy composites for automotive components. By reinforcing cast alloys with rigid ceramic foams, improved strength and creep resistance at high temperatures is possible. The process involves preparing open cell polymer-derived ceramic foams in air at 200-300°C from Si/SiC filled polysiloxane by mixing the polymer precursor powder with Si/SiC.

The next step involves pyrolysis in nitrogen at 1000-1200°C to convert the polysiloxane. The ceramic foam, which has a high interconnectivity of pores ranging in diameter from 0.5 to 2 mm and a compression strength exceeding 3 MPa, is then infiltrated with molten metal at 680°C and 86 MPa using a squeeze casting process. A dense metal/ceramic interpenetrating phase composite with superior mechanical properties at temperatures above 100°C is produced. [5]

2.1 Composites for Space:

Several programs in the U. S. and Japan are looking at composites for future supersonic space vehicles. Japan's ESPR project is developing a Si-Zr-C-O/SiC composite for combustor liners with the goal of reducing CO_2 emissions by 25%. For this project, Kawasaki Heavy Industries has developed a process that involves coating a fibre preform by chemical vapour infiltration, impregnating the perform with a glass powder slurry, and then drying the part. The final step involves a combustion reaction. A glass coating helps seals the pores and microcracks thereby improving mechanical properties.

Other ESPR-funded research at Ishikawajima-Harima Heavy Industries is developing a SiC/SiC vane for gas turbine engines. A hollow airfoil structure integrated with a 300 X 130 mm inner platform has been designed and manufactured. The process involves weaving a fibre performs, applying an interface coating via CVI, and several additional reactions involving CVI and pyrolysis. Before the final reaction occurs, the part can be easily machined. Creep rupture in an oxidized environment at elevated temperatures can be improved by adding an inhibitor during the process. SiC-based composites with a mullite coating are also being considered for turbine shrouds and have shown suitable thermal durability in preliminary tests.

At NASA Ames Research Center, HfB_2 and ZrB_2 are candidates for leading edge applications on future hypersonic reentry vehicles because of their high melting temperatures and good oxidation resistance. Current work focuses on compositions of HfB_2 with a SiC particulate reinforcement. Japan's National Aerospace Laboratory is also evaluating ceramic matrix composites for air breathing engines being designed for two-stage to orbit reentry space vehicles. [5]

2.2 Composites on Earth:

Composites show promise for many earth-based applications. Ceramic armour of monolithic form is already being used in various systems, from personnel protection to military vehicles. Boron carbide has found application in lightweight armour because of its high hardness and low density. To improve its ballistic performance, researchers are investigating increasing its fracture toughness by adding inert and/or reactive compounds (such as SiB_6) or by altering its composition. B_4C/SiB_6 composites have been made with bulk densities, elastic moduli and Vickers hardness up to 2.68 g/cm^3, 400 GPa and 25 GPa, respectively.

Silicon carbide is also being reinforced with shape-modified SiC fibres for armour, as well as tungsten carbide with diamond. SiC platelets are being evaluated as a reinforcement for alumina. At a 14 vol% SiC content, Al_2O_3/SiC composites have a toughness of 19 GPa and a hardness of 5 MPa-m$^{1/2}$. SiC is being combined with B_4C as well for laminate composites. By proper design, high compressive residual stresses can be achieved in 150-micron thick B_4C-SiC based layers and low tensile residual stresses in 1000-1500 micron thick B_4C layers. C/C-SiC composites also show promise for lightweight armour in automotive and aircraft applications. [5,8]

2.3 Composites for Aeronautical Industries:

Some typical applications of composite materials in aerospace industries are shown in Fig-1 [3,11]

2.4 Composites for Industries :

For the automotive industry, C/C-SiC brake disks are already being used for several luxury/high performance cars, including a 2000 limited edition DaimlerChrysler model and a 2001 series for Porsche. Research at the German Aerospace Center has improved these discs by applying a coating based on Si-SiC called SiCraleen during fabrication.The discs are made by hot pressing half shell C/C preforms pyrolysis at 900-1600°C, joining the two halves and then infiltrating them with liquid Si. In situ joining via reaction bonding during siliconizing also allows production of complex parts.The improved discs have almost no wear and are expected to last a lifetime or 300,000 km for a car and reduce costs by 75-80% compared to C/C disks. No distortion or corrosion has been observed. In 2002 a new production plant for these disks was built, which currently can produce 35,000 disks per year. By 2004-2005, production is expected to increase to 300,000 disks per year. However, process costs still need to be reduced since the discs are quite expensive (7500 Euro for a 16.5 kg weight reduction). If costs come down the discs may have application as service brakes for cars/planes and emergency brakes for trains.

Other research at the Centre is developing C/C-SiC composites that incorporate hard particles like diamond, cubic BN and B_4C for cutting tools. Such tools can provide higher operating temperatures and higher cutting speeds. They also do not require cooling and increase safety. After the particles are coated with resin, they are laid up in a mould with sheets of C-fabrics and hot pressed at 20 bar and 200°C. Pyrolysis at 900°C in an inert gas is the next step, followed by infiltration with Si at 1600°C under vacuum.

The carbon fibers and the hard particles are strongly bonded by a heat resistant SiC and the particles maintain their sharp edges during manufacture. Diamond particles also retain their composition, even though diamond converts to graphite above 1200°C. The size and amount of particles must be minimized since a higher content and larger particles increases porosity. These composites also show potential for lightweight armour protection.

Another area where composites are being developed and tested is industrial gas turbine components. Solar Turbines (San Diego, Cal.) has been evaluating SiC, SiC/SiC, and oxide/oxide composites for application as combustor liners under several programs sponsored by the DOE Office of Industrial and Power Technologies. The goal is to produce components of low cost, reduce emissions and improve energy savings. Ceramic materials allow an increase in turbine rotor inlet temperature (TRIT), which reduces energy consumption.

SiC/SiC liners have survived more than 52000 h of full load operation at 9 field installations (4 years without any unscheduled shutdowns, lasting 14,000 h and 15,000 h at two sites) and have achieved 30% efficiency, a TRIT of 1121°C, and low emissions (NO_x <15 ppm, CO<10 ppm). An environmental barrier multi-layer coating has been developed based on a composition combining barium aluminosilicate and mullite.

However, these composites are limited to stationary parts such as liners, seal rings, nozzles, and vane rings and cannot be used for long-life rotating parts. Cost is still three to six times that of metal parts. Therefore, process costs must still be reduced although braided tubes can make multiple vanes. Another challenge is to extend the durability of the coatings. Although oxide/oxide composites failed in earlier tests, testing of oxide/oxide composites, which have a temperature limit around 1100°C, is resuming this year. Despite these many challenges, it is expected that the gas turbine industry will be switching to ceramic matrix composites in the next 5-10 years to meet future energy and emissions requirements.[5,11]

2.5 Composites for Nuclear Applications:

In addition to gas turbines, SiC/SiC composites are being considered for advanced nuclear applications such as fusion blanket/first wall structures and fission core structures/liners. These materials are promising because of the radiation resistance of the SiC beta phase and their excellent high-temperature fracture, creep, corrosion and thermal shock resistance. Fracture toughness is on the order of 25 MPa-m$^{1/2}$.

The Generation IV International Forum - which is composed of the following countries: U. S., UK. Switzerland, South Korea, South Africa, Japan, France, Canada, Brazil, and Argentina - hopes to deploy new advanced nuclear systems by 2030. Six systems are being considered: gas fast or lead-cooled, molten salt, sodium-cooled, supercritical water cooled, and very high temperature (VHT) reactor. The VHT reactor will operate at 1800°C, leading to high thermal efficiency. These types of reactors are also ideal for hydrogen production and have inherent passive safety.

Japan's METI (Ministry of Economy Trade and Industry) has provided $7 million in 2000, $13 million in 2001, $91 million in 2002, and $43 million in 2003 for basic research in this area. At Kyoto University, a four-year $3-million program involves fundamental research on materials and design, near net shaping, and joining methods. So far the researchers have developed a process called NITE (nanoinfiltration and transient eutectic-phase process) that can produce good mechanical properties and various shapes. They are also developing a SiC interface that can be tailored for environmental stability.

Despite SiC/SiC's excellent radiation stability, the effect of irradiation remains a key technical issue. Irradiation can reduce baseline properties via an atomic displacement or chemistry change, and irradiation induced densification can cause debonding of the interface. This debonding can be avoided by using a crystalline fiber coated with pyrolytic C. Radiation can also produce a cascade structure similar to metals but with more defects and dislocation loops.

Current performance limits are: a maximum temperature 1000°C, a resistivity of 10-15 W/m-K, and a strength of 100-200 MPa as irradiated. Creep limits are unknown and because lifetime depends on creep strain, these limits must be determined. Other issues include production cost, impurity control, joining, and chemical compatibility.

As has been seen, costs continue to be a major challenge in achieving commercialization for ceramic matrix composites in the applications described. Although there has been some progress, more reductions are needed for continued success. [5]

3. Concluding Remarks:

From the discussion in the previous paragraphs, following conclusions may be drawn.

- Composites have unique advantages over monolithic materials, such as high strength, high stiffness, long fatigue life, low density, and adaptability to the intended function of structure.
- M Cubed Technologies, Inc. (Newark, Delaware) has developed a cost-effective, pressure-less metal infiltration technique called PRIMEX for manufacturing large complex ceramic-metal composite components including SiC/Al-Si, SiC/Si, B_4C/Si, SiC/Al, graphite/Si, graphite/Al-Si, and B_4C/Si/SiC.
- Japan's ESPR project is developing a Si-Zr-C-O/SiC composite for combustor liners with the goal of reducing CO_2 emissions by 25%.
- At NASA Ames Research Center, HfB_2 and ZrB_2 are candidates for leading edge applications on future hypersonic reentry vehicles because of their high melting temperatures and good oxidation resistance.It is developed, C/C-SiC composites that incorporate hard particles like diamond, cubic BN and B_4C for cutting tools.
- Composite ha found widely application in Aerospace industry.
- Boron carbide has found application in lightweight armor because of its high hardness and low density.
- SiC/SiC composites are being considered for advanced nuclear applications such as fusion blanket/first wall structures and fission core structures/liners.

From the above conclusions it is very clear that composite material have wide application due to its special properties, which is not possible in monolithic material. Therefore Researcher has wide scope for new development in this area. Hence all advanced countries, is taking a big interest in composite materials,

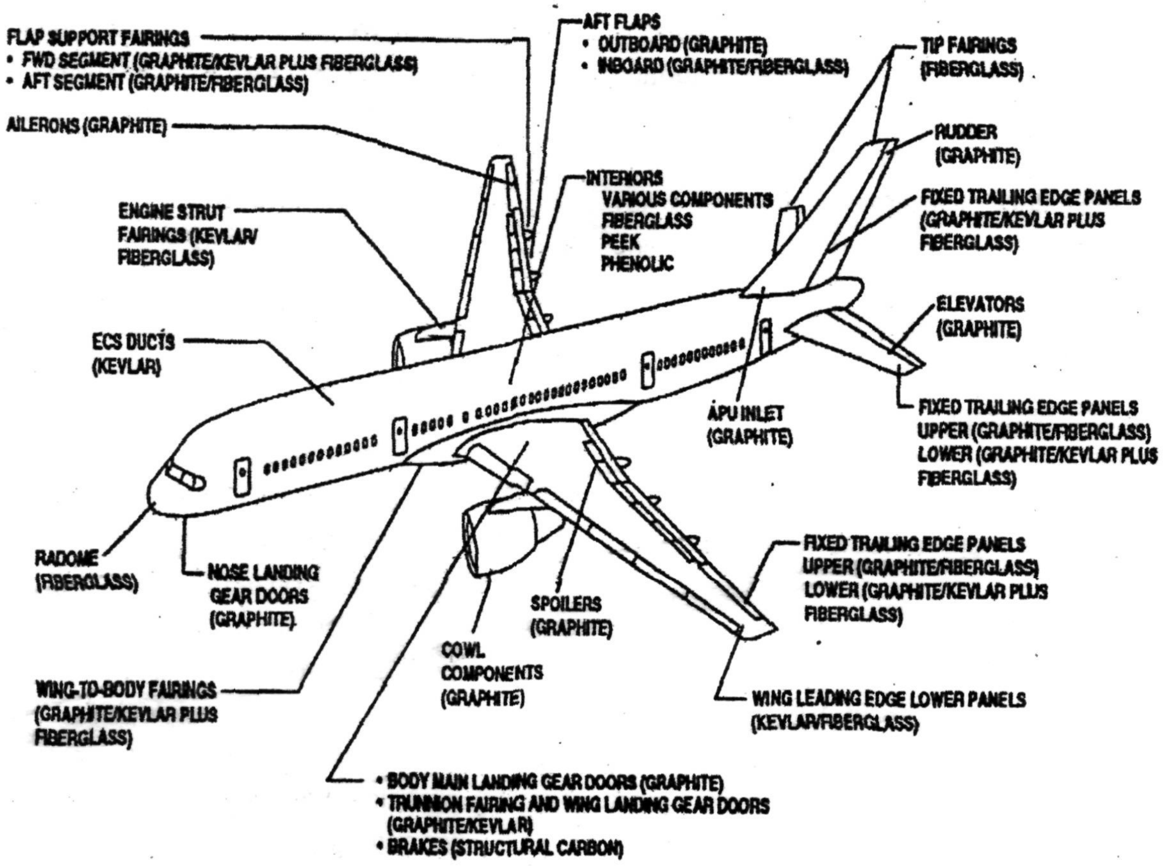

Fig. 1 Diagram illustrating the various components of the Boeing 757 aircraft made of composite materials. (Courtesy of Boeing Commercial Airplane Group.)

which many people see as 'the materials of the future'.

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