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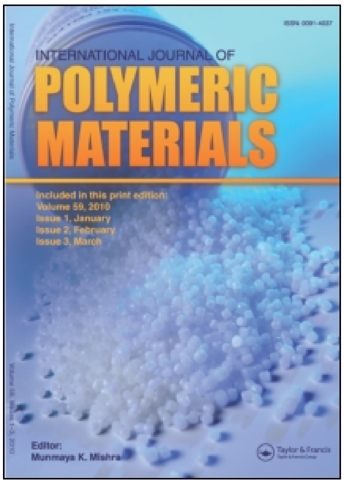

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Gold Ribbon Abstracts

CERAMICS

GEOPOLYMERS: NEW INORGANIC POLYMERIC MATERIALS

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In the aftermath of various catastrophic fires in France between 1970–73, which involved common organic plastics, I focussed my research on non-flammable and non-combustible plastic materials and founded a private research company in 1972, which is today called CORDI-GÉOPOLYMÈRE. During my search for new inorganic polymer materials, I was struck by the fact that simple hydrothermal conditions govern the synthesis of some organic plastics and also heat-resistant mineral feldspathoids and zeolites. The scientific and patent literature indicate that, prior to 1978, the geochemistry that yields the synthesis of zeolites and molecular sieves had not been investigated for producing mineral binders and mineral polymers. I proceeded to develop amorphous to semi-crystalline three-dimensional silicoaluminate materials, which I call "geopolymers" (mineral polymers resulting from geochemistry). These reactions are of the poly(sialate), poly(sialate-siloxo)/disiloxo) types (Figure 1). Geopolymerization involves a chemical reaction between various alumino-silicate oxides (Al^{3+} in IV–V fold coordination) with silicates, yielding polymeric Si—O—Al—O sialate bonds like the following:

$$2(Si_2O_5, Al_2O_2) + K_2(H_3SiO_4)_2 + Ca(H_2SiO_4)_2 = (K_2O, CaO)(8SiO_2, 2Al_2O_3, nH_2O)$$

Geopolymers involved in materials developed for industrial applications are noncrystalline. Nuclear magnetic resonance ^{27}Al and ^{29}Si (MAS-NMR) spectroscopy provide some insight into their molecular frameworks. Other than my archaeological research on ancient cements, my research has been purely industrial. Thus, almost all of the scientific literature concerning geopolymerization is found in the patent literature.

THE INDUSTRIALIZATION OF GEOPOLYMERIC PRODUCTS

My subsidiary company, GEOPOLYMERE, sarl (France) was founded in 1984 in association with my brothers Michel and Nicolas Davidovits. Our products include advanced mineral binders that withstand harsh environmental conditions, high-temperature stable GEOPOLYMITE® binders and GEOPOLYCERAM® compounds, fireproof carbon-geopolymer composites. Some U.S. Patents are: J. Davidovits U.S. 3,950,470 (1976); 4,349,386 (1982); 4,472,199 (1984); 4,859,367 (1989); 5,288,321 (1994); J. Davidovits and J. J. Legrand U.S. 4,028,045 (1977); N. Davidovits, M. Davidovits and J. Davidovits U.S. 4,888,311 (1989); and other patents granted in 1994 œ pending.

In the USA, LONE STAR INDUSTRIES Inc. began product development in 1983, and in 1988 this company introduced PYRAMENT®, a new class of special blended cements, U.S. Patents: J. Davidovits and J. L. Sawyer, U.S. 4,509,985 (1985); R. F. Heitzmann, M. Fitzgerald and J. L. Sawyer U.S. 4,642,137 (1987); R. F. Heitzmann, B. B. Gravitt and J. L. Sawyer U.S. 4,842,649 (1989).

In Germany, HÜLS TROISDORF AG began product development in 1982 (Dynamit-Nobel AG).

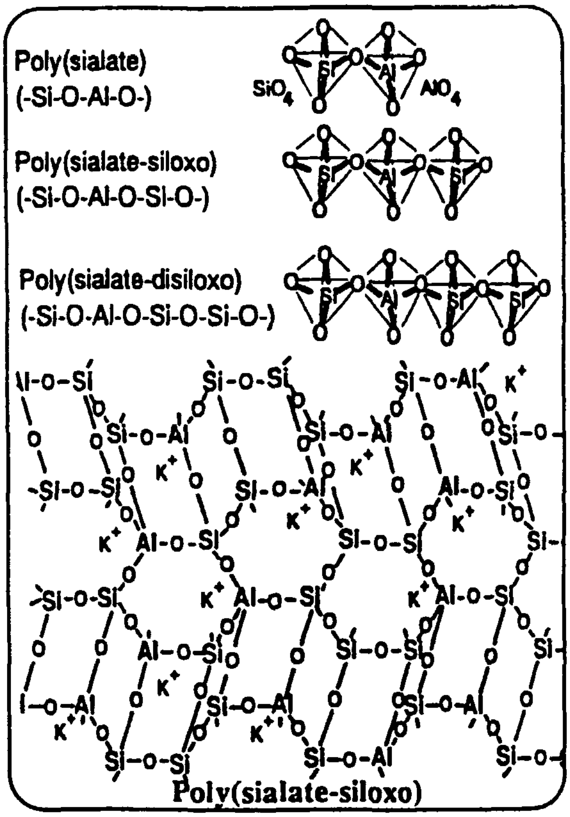

FIGURE 1 Chemical structure of Poly(sialate), Poly(sialate-siloxo), Poly(sialate-disiloxo) and three-dimensional Poly(sialate-siloxo) "Geopolymers."

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Their products were introduced in 1990 and they include TROLIT® binders, industrial high-temperature insulation WILLIT®-Foam and Willit®-Composite, U.S. Patents: K. H. Neuschaffer, H. W. Engels, H. J. Gebert, R. W. Laube and G. Zoche, U.S. 4,522,652 (1985); N. H. Neuschaffer, P. Spielau, G. Zoche and H. W. Engels, U.S. 4,533,393 (1985); K. H. Neuschaffer, P. Spielau, H. W. Engels and G. Zoche, U.S. 4,608,795 (1986).

NEWLY INDUSTRIALIZED GEOPOLYMERIC PRODUCTS

In Europe, the multidisciplinary BriteEuram industrial research project GEOCISTEM, is preparing to introduce acid-resistant Poly(sialate-siloxo) cements for restoring sites highly contaminated with uranium mining waste (WISMUT sites in former East Germany). This project also provides new geopolymeric cements that can help address the problem of global warming by reducing 80% of the CO_2 emissions produced by the cement industries.

ALUMINOPHOSPHATE-BASED MOLECULAR SIEVES NEW GENERATIONS OF CRYSTALLINE MICROPOROUS INORGANIC MATERIALS

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Molecular Sieves are a class of industrial products used widely throughout the Chemical Process Industries. They were introduced commercially by Union Carbide Corporation as a new class of materials in 1954 following the discovery of several novel synthetic zeolite molecular sieves by UCC researchers Robert M. Milton and Donald W. Breck in the late 1940's and early 1950's. Based on these early materials' discoveries and their commercial introduction, an immense science, technology and business have flourished. In 1993 over five hundred and fifty metric tons of molecular sieves were manufactured and sold worldwide by over a dozen suppliers, with revenues of over six hundred million U.S. dollars. Over ten thousand chemists and engineers are working in the field today. The Molecular Sieve industry is exemplar of a major success by U.S. industry in the innovation and commercial development of novel materials.

Molecular sieves are microporous crystals that contain pores and cavities the size of molecules. Molecules smaller than the pores enter the material and are adsorbed or trapped inside the cavities, while larger molecules pass by. The ability to discriminate molecules on the basis of size as well as polarity has led to hundreds of applications with three basic functions: adsorbents, catalysts and ion exchangers. As adsorbents, molecular sieves dry and purify natural gas and keep refrigerants in refrigerators and air conditioners from freezing. As catalysts, they are used in the petroleum refining processes to produce gasoline, diesel fuel and aircraft jet engine fuel. Their ion exchange properties are used to clean up nuclear wastes and replace environmentally suspect phosphates in household detergents. Very recently, molecular sieves were introduced in a new application based on their ability to deodorize.

Prior to 1980 most known and all commercial molecular sieves were zeolites. Zeolite molecular sieves are crystalline, hydrated metal aluminosilicate compositions, consisting of a three-dimensional framework or lattice built up by linking silicon oxide, SiO_4, and aluminum oxide, AlO_4, tetrahedra. The intracrystalline or lattice voids contain exchangeable metal cations and water. Some three dozen structures with different tetrahedral linkages and lattice arrangements were known in the literature of which only a handful achieved commercial use. Recognizing that historically the business and technology was materials driven, Union Carbide Molecular Sieve business management focused on a new materials strategy in the late 1970's with a target of achieving a step change in growth of the business. As part of that strategy, management challenged the materials research group to discover the next generation of molecular sieve materials.

The research group first set up a team consisting originally of Brent Lok, Steve Wilson, and this author as leader. The team developed a strategy to look at new framework or lattice compositions other than the then-known oxides of aluminum and silicon. The broad strategy viewed the entire Periodic Table of Elements as the potential scope for the new compositions and structures. The elements were ranked based on crystal chemical principles and intuition, and the oxides of aluminum and phosphorus chosen for initial experimentation. After months without success, the team decided to try synthesis conditions well out of the mainstream of all precious molecular sieve synthesis. With that unconventional approach they hit the jackpot. Within less than six months, over a dozen structures were discovered, and a new family of aluminophosphate molecular sieves emerged.[1] The family was called "ALPO" after the chemical symbols for aluminum, phosphorus and oxygen.

Expanding the strategy to add other elements to the base aluminophosphate composition, silicon was added successfully generating the "SPAO" family[2] (silicon, aluminum, phosphorus, oxygen), and a number of metal elements, resulting in the "MeAPO" family[3] (metal, aluminum, phosphorus, oxygen). By the mid 1980's the Synthesis Research group, then much larger, had successfully incorporated thirteen different elements into the AlPO framework, and had discovered over two hundred compositions and more than two dozen structures. Some thirty patents had been filed covering the new proprietary materials. The new generation was called the $AlPO_4$-based molecular sieves,[4] and is generally recognized as a landmark discovery in molecular sieve and inorganic materials.

With a windfall of new materials, Carbide developed a business strategy to fully exploit the discovery. UOP, a company owned by AlliedSignal Corporation, was a world leader in Application and Process Technology serving the petroleum and petrochemical industry worldwide. Both Carbide and AlliedSignal saw the opportunity to wed the Carbide new molecular sieve materials with the UOP process technology, and formed a joint venture, the "new" UOP, in 1988. Several commercial or near commercial processes have been developed utilizing $AlPO_4$-based molecular sieves as catalysts that should lead to more environmentally friendly chemicals and fuels. Chevron has commercialized a new "Isodewaxing" process[6] using a SAPO-based molecular sieve for converting waxes to lube oils and fuels with advanced performance, and environmental and safety benefits.

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DIRECT COAGULATION CASTING (DCC) A NEW CERAMIC FORMING TECHNIQUE

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SUMMARY

A new ceramic green body shaping technique (direct coagulation casting) has been developed, which combines the positive features of the traditional forming methods slipcasting and injection moulding but avoids their drawbacks. It allows the near net shaping of complex ceramic parts by pressureless casting of aqueous ceramic suspensions in low cost moulds. The suspension solidifies inside the mould due to an enzyme catalyzed reaction which leads to coagulation. The wet, rigid green bodies are dried outside the mould and sintered. Since the forming process takes place without pressure, no expensive moulds and tools are required. Therefore it is also suited for rapid prototyping. Complex, defect-free, high-density structural ceramic bodies of alumina, zirconia, silicon carbide and other ceramic materials as well as composites were fabricated.

BACKGROUND

For many applications of functional and structural ceramics the production of complex-shaped components is often time consuming and costly. The today's processes for fabrication of such complex components are slip casting, including pressure casting and injection moulding.

Slip casting, a rather cheap process is principally not suited for fabrication of thick-walled components (>1.5 cm) from micronized ceramic powders since this results in inhomogeneous textures.

Injection moulding on the other hand is a rather expensive process due to considerable costs for equipment and metallic moulds. Furthermore, the quality of the formed components is often poor due to inhomogeneous microstructures, which result from the burnout of high amounts (up to 50 vol.%) of thermoplastic binders. Only relatively thin-walled components can be economically fabricated.

CONCEPT OF DIRECT COAGULATION CASTING

The new process direct coagulation casting (DCC) uses a mechanism of coagulating a slurry by internal pH change or by internal salt generation to produce rigid green bodies. In this process a slip of low viscosity is cast into a mould. Then the pH of this slip or its ionic strength is changed by a controlled time-delayed, enzyme catalyzed reaction. This leads to an increase of the viscosity by 6–8 orders of magnitude and to the solidification of the cast suspension to a viscoelastic body. After this consolidation the still wet green body can be removed from the mould and dried without introducing defects. The new forming process is characterized by near net shape capability, high quality and homogeneity of the green- and sintered bodies. Only small amounts (<1%) of nontoxic organic additives are needed. Since the forming process takes place without pressure, no expensive moulds and tools are required.

As DCC is exclusively based on aqueous suspensions, drying times are comparable to those of slip casting and orders of magnitudes faster and easier than the binder burnout process of injection moulding. In comparison to slip casting, where the green part always will show inhomogeneous green densities, the consolidation process of the green body is a homogeneous process throughout the part. Isotropic shrinkage occurs during the subsequent sintering process. Due to the same reason, components with thick and thin cross sections in the same part can be made defect free. Figure 1 positions the potential of this process in respect to complexity in shape of the parts and average maximum component thickness.

Today the process can be applied to a large variety of ceramic powders such as alumina, zirconia, zirconia toughened alumina, silicon nitride, silicon carbide, cordierite, zinc oxide and silicon dioxide as well as composites. It also can be combined with polymeric binders which will gel upon the enzyme catalyzed reaction.

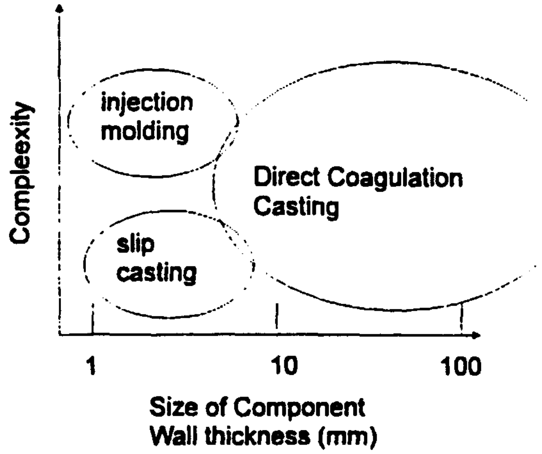

FIGURE 1 Comparison of different forming techniques in respect to complexity and wall thickness of components.

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CERAMIC SCINTILLATORS FOR ADVANCED X-RAY DETECTORS IN CT SCANNERS

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and
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Medical imaging has grown to be a salient part of the health care field being discussed in Congress right now. One of the diagnostic procedures that revolutionlized imaging technology was the computerized tomography (CT) x-ray scanner, shown schematically in Figure 1. This scanner is now routinely used for both emergency trauma care and for detailed body studies including 3D images.

HiLight™ ceramic is a scintillator material developed specifically for use in the CT scanner's x-ray

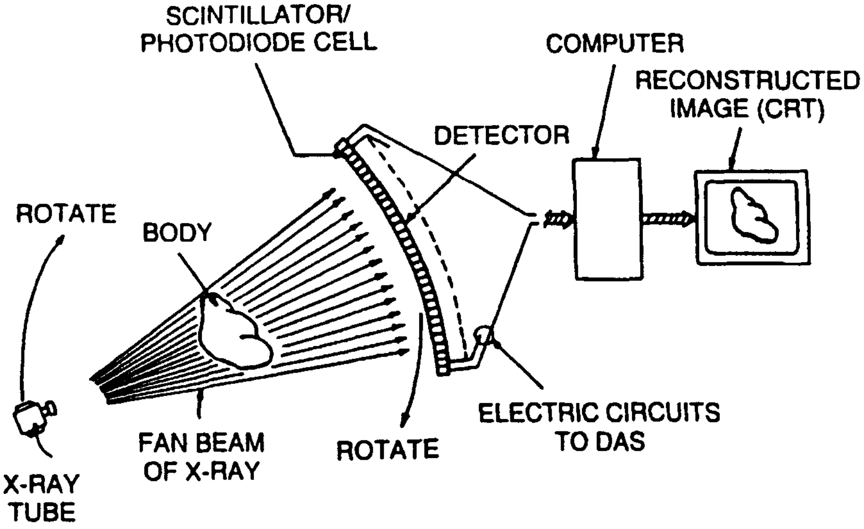

FIGURE 1 Schematic diagram of a rotate-rotate CT scanner utilizing a fan beam of x-rays passing through the body, and striking a HiLight detector. The electrical signals are sent to a data acquisition system (DAS) for digitization and image reconstruction.

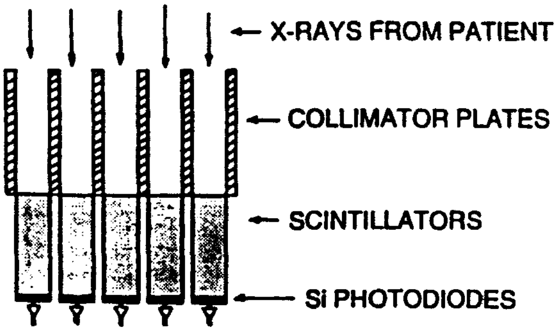

FIGURE 2 Top view of fine detector cells showing the tungsten collimator plates and the scintillator elements optically-coupled to the Si-Photodiodes.

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detector subsystem, which consists of nearly 1000 side-by-side ceramic scintillators as primary x-ray sensors arranged in an arc behind tungsten collimator plates that minimize x-ray scatter. These scintillators are small, about the size of a match stick, but are machined to very high precision. Behind each scintillator is a tiny light-sensitive photodiode, or "electric eye," as shown in Figure 2. When struck by x-rays that have passed through the patient's body, the ceramic elements glow (scintillate) with an intensity proportional to the number of x-rays they absorb, producing varying levels of visible light that are "read" by the photodiodes. Each photodiode produces an electrical charge proportional to the intensity of light produced by the HiLight scintillator. These electrical signals, nearly a million of them per scan, are fed into a computer which reconstructs a cross-sectional image of the body section being examined.

In the early 80's a small research program was initiated at the GE Corporate R&D Center to develop a new scintillator, specifically for the demanding CT requirements, with improved performance over existing single crystal scintillators. By combining carefully-controlled phosphor composition and doping technology with innovative technology on transparent, polycrystalline ceramics, a proprietary "rare-earth-doped, yttria-gadolinia ceramic scintillator" was discovered and patented. The "host" is a solid solution of yttria and gadolinia selected for high optical clarity in the visible region and high x-ray stopping power. A small amount of rare earth "activator," europia, is employed to provide high scintillation efficiency. Shortly after this initial invention, a "scintillator" team consisting of individuals from GE Corporate R&D and GE Medical Systems was formed to prove-out this new scintillator technology and fully transition this discovery from the applied research stage to the development/prototype stage. During several years of cooperative effort considerable knowledge was gained from a variety of scale-up processes involving powder synthesis, ceramic processing, control of impurities and scintillator property development.

Property testing of scintillator/photodiode modules for prototype x-ray detectors revealed that the luminescent afterglow and radiation damage properties of the ceramic scintillator had to be further reduced and made more uniform from element-to-element to be acceptable for a designed quantitative detector with sensitivity greater than 1 count in a 1000. In a CT scanner, nonuniformly high afterglow and radiation damage result in unacceptable image artifacts. In order to overcome these problems, additional R&D effort on improved powder preparation, processing, sintering conditions and the use of small amounts of proprietary additives all permitted the discovery of means to reduce and control these two key scintillator properties. With the help of chemists, physicists, materials-electrical-mechanical engineers and designers, and computer scientists from such groups as Ceramics R&D, Applied Science Laboratory, Software & Systems Engineering, and X-Ray Detector Engineering and Manufacturing, a relatively successful transition occurred during the scale-up phase of mass production of high quality ceramic scintillators for advanced medical x-ray detectors.

Advanced CT scanners with the HiLight solid state x-ray detectors were evaluated at a number of clinical test sites in the middle 1980's. Members of the radiological community judged the body images to have markedly enhanced overall quality at reduced x-ray dose. The first commercial production systems were sold in 1988, and since then early 2000 CT scanners equipped with the special HiLight ceramic detectors are now in use in hospitals and clinical sites around the world.

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THE DEVELOPMENT OF METHODS TO PRODUCE DIAMOND AT ATMOSPHERIC PRESSURE BY CVD

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HISTORICAL BACKGROUND

Synthesis of diamond by artificial methods had long been a dream of mankind and it was achieved in 1954 under the conditions of high-pressure (50,000 atm) and high-temperature (up to 1600°C) (in the thermodynamically stable region of diamond, HP-HT method) by researchers of General Electric Co. and of ASEA Co. However, as the HP-HT method requires large and expensive equipment, there was also a desire to synthesize diamond at lower pressures, i.e., below 1 atm. However, synthesis at such low pressures was more difficult because diamond is metastable and graphite is stable at such conditions. Few researchers, mainly in U.S.A. and Soviet Union, had tried metastable growth of diamond from the early years by methods such as the decomposition of methane gas on diamond powders and deposition of carbon ions on solid substrates, as revealed, for example, by the U.S. patents of Eversole in 1959. However, it was difficult to prove the presence of new diamond since the substrate was diamond, and the product could have been amorphous. In 1976 and later in 1981, a Soviet group reported a success in the synthesis of crystalline diamond by chemical vapor transport methods which uses solid carbon materials (graphite) as a carbon source but the details of the synthesis method was not made open until 1990 due to the inhibition by the Soviet government.

RESEARCH WORKS IN NIRIM

We started research on low pressure synthesis of diamond in 1974 (partly from 1972), beginning with studies on the deposition of carbon by sputtering of graphite, decomposition of methane on diamond powders, chemisorption of foreign atoms on diamond powders. The work of the Soviet group had suggested the importance of the activation of the gas phase for the deposition diamond. We tried to deposit diamond from a mixture gas of hydrocarbon and hydrogen activating the gas phase thermally by a heated filament of tungsten. After many experiments changing gas composition, gas pressure, filament temperature, etc., we were finally able to obtain small crystallites of diamond on silicon, molybdenum, etc., at low pressures (0.01–0.2 atm) and at relatively low temperatures (700–1000°C). This method which is now called the hot filament method (HF method) is cheap and easy to operate. Today in Japan even junior high school students are making diamonds by this method. After the success by the HF method, we started the experiments of diamond synthesis by gas activation using microwave discharge, which was known to generate the highest density plasma among many glow discharges. The microwave method gave as good quality diamond as the HF method did. Even now, these two methods are the most popular for commercial diamond synthesis from the gas phase. These successes in NIRIM made it clear that diamond could really be synthesized even at low pressures and a boom of research of diamond synthesis from the gas phase started in Japan and spread to the U.S.A., and then to all over the world.

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APPLICATIONS OF LOW-PRESSURE SYNTHESIZED DIAMOND

Is diamond attractive only because it is eminent as a gem stone? It is certainly not. Diamond has many excellent properties as will be shown in the following. It has the highest hardness, highest elastic constants, highest speed of sound, highest thermal conductivity (at room temperature, 6 times as high as copper) of all the materials on the earth. It is transparent in the wide range of wavelength (from infrared through visible to ultraviolet), it has high carrier (hole) mobility and low dielectric constant, and other excellent properties, which suggest it can be most advanced materials for various use. Application of these properties became possible by the success in synthesis from the gas phase, because the HP-HT synthesis method cannot make diamond in the form of thin films or coatings. Nor can it make films and highly pure crystals. Moreover, to make diamond in film form is essential for applications in electronic materials.

Diamond coated cutting or grooving tools are now used commercially for machining materials. Researches for many applications such as an UV and high-energy beam detector, high-temperature thermistor, field effect transistor, cold cathode electron emitter, thermal management materials have also been undertaken. In the latter use, CVD diamonds have led to free standing diamond plates of 4 inches by 4 inches by 2 mm. The quality of diamond films from the gas phase is now comparable or better than that of natural ones. Key technologies for the above applications, such as the synthesis of single-crystal films, are also progressing well owing to the world-wide interest in this research area. Not only as a gem stone for women, but also for materials scientists diamond will continue to be the representative of solids with covalent bonding and as a material with several unique properties mentioned above.

COMPOSITES

BREAKTHROUGH IN INORGANIC COMPOSITES TECHNOLOGY

MARC S. NEWKIRK
President and CEO, Lanxide Corporation

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Over the past eleven years Lanxide Corporation team members have invented, developed, patented and commercialized fundamentally new process technologies that enable the low-cost manufacture of high performance inorganic composites. High performance inorganic composites are a significant new class of materials that combine the advantages of ceramics as a class of materials with those of metals. Lanxide's new technologies are based upon the discovery and application of fundamentally new behavioral characteristics of molten metals.

The new technology has two basic elements. The first element is a process technology for creating reinforced ceramic components utilizing a serendipitously discovered phenomenon called "directed metals oxidation." Lanxide's DIMOX™ directed metals oxidation process literally "grows" a ceramic matrix through a reinforcing material, such as ceramic particles or fibers, to yield net or near-net shaped reinforced ceramic components. The ceramic matrix is generated by the reaction of a molten metal with an oxidizing atmosphere in a unique fashion where molten metal is transported continuously through its own oxidation reaction product, supporting further oxidation reaction. The process is generic, applying to many metals and oxidizing reactants yielding a wide range of materials. The process is typically conducted at atmospheric pressure and relatively low temperatures using commodity purity starting materials. Articles of virtually any overall size, shape or thickness may be produced.

The second element of Lanxide's inorganic composites technology base involves a method for creating reinforced metallic components using a process tradenamed PRIMEX™ pressureless metal infiltration. This process applies a serendipitous discovery of a mechanism which can be triggered so as to cause a molten metal to spontaneously infiltrate a shaped, porous reinforcement of ceramic particles or fibers to yield net or near-net shaped ceramic-reinforced metallic components. As with the DIMOX™ reinforced ceramic technology, the PRIMEX™ reinforced metals process is conducted at atmospheric pressure and relatively low temperatures, utilizing commodity purity starting materials. Parts can be produced without size or shape limitation.

A variant of the PRIMEX™ pressureless metal infiltration process is the PRIMEX CAST™ foundry process for making castable ceramic-reinforced metals. In this variant, molten metal is spontaneously infiltrated into an unbonded mass of ceramic particulate, and the resulting molten composite is cast to shape using traditional casting processes such as die casting, investment casting, sand casting or permanent mold casting.

Utilizing Lanxide's various processes, materials can be produced with combined properties specifically engineered to suit the wide ranging needs of a broad array of industries. The composites exhibit superior combinations of cost and performance characteristics compared to ceramics or metals.

Lanxide has aggressively pursued patent protection for its inventions, which, because of their fundamental nature, have been capable of supporting broad patent claims. More than two thousand patents involving more than eighty inventors have been issued or allowed to Lanxide around the world to defend its discoveries, with more than a thousand additional patent applications pending.

The new technologies yield components which enable major improvements in product performance capabilities, manufacturing productivity, energy consumption and environmental aspects across basic industries. Lanxide is commercializing its technology through individual business units focused upon the different market segments that the technology can impact. World-class industrial partners and backers have been attracted, supporting the development and exploitation of the breakthroughs. These include Alcan, DuPont, Kanematsu, Hercules, Nihon Cement Company and private investors. To date, ten commercial businesses have been formed in a combination of joint ventures and wholly-owned subsidiaries, with product adoptions now achieved in the electronics, steel processing, mining, cement, electric power generation, medical, semiconductor manufacturing, fiber processing, incineration, chemical process, automotive and other industries.

COMPOSITE TRANSDUCERS

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Materials Research Laboratory, Pennsylvania State University, University Park, PA 16802

Electromechanical transducers convert electrical energy into mechanical energy, or mechanical energy into electrical energy. Piezoelectric ceramics such as PZT (lead zirconate titanate) are often used as transducers because of their large electromechanical coupling coefficients. These transducers are used for imaging human hearts and unborn babies; for finding fish and submarines in the ocean; for knock sensors and door buzzers in automobiles; for spark igniters in lawn mowers and outdoor cooking grills; for speakers, channel selectors, filters and transformers in audio systems and television sets; for the precise positioning required in optical scanners and electron microscopes; and as high-force actuators for printers and ink jets.

In many of the vibration-control systems, the transducer is used both as a sensor (the direct piezoelectric effect) and as an actuator (the converse effect). In this way it is able to detect vibrations, and then cancel them. These are called "smart" systems. The optical problems of the Hubble Telescope were remedied with the assistance of smart piezoelectric actuators.

The focus of our research program during the past 20 years has been the optimization of piezoelectric transducers for this myriad of applications. We have done this by making many types of composite transducers in which piezoelectric ceramics are combined with polymers and metals to optimize performance. PZT has very large piezoelectric coefficients, but in other ways its properties are deficient: the acoustic and electric impedances are often too high and the hydrostatic voltage sensitivity, too low. Greater mechanical flexibility and lower electrical drive voltages are also desirable. Hysteresis, brittleness, and aging effects are also problems, and for actuator applications there is often a force-displacement trade off. PZT ceramics produce very large forces but only minuscule displacements, usually in the micron range.

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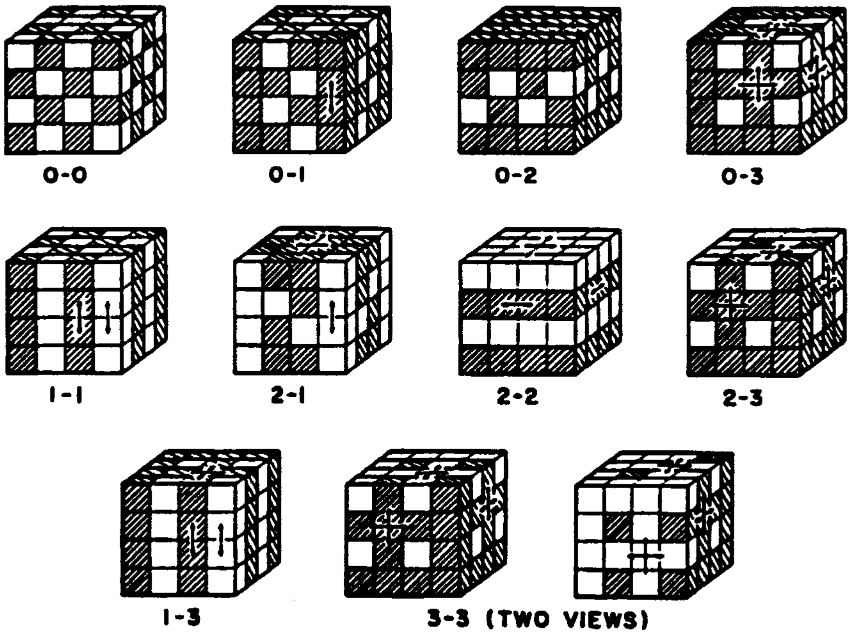

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1-3 3-3 (TWO VIEWS)

FIGURE 1 Connectivity patterns for a diphasic solid. Each phase has zero-, one-, two- or three-dimensional connectivity to itself. In the 3-1 composite has, for instance, the shaded phase is three-dimensionally connected. Arrows are used to indicate the connected directions.

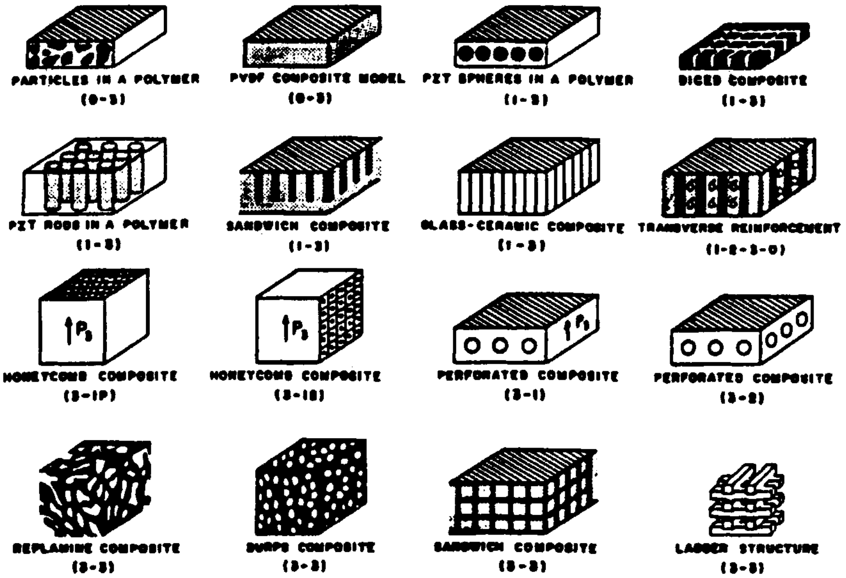

FIGURE 2 Schematic diagram of various types of composites with different connectivity.

To solve these problems we have fabricated composite piezoelectric transducers in a number of different "connectivity" patterns. Connectivity is defined as the number of dimensions in which a material is self-connected. A composite in which parallel fibers of one material are embedded in a three-dimensional matrix of a second material is called a 1-3 composite. Multilayer devices in which two materials are laminated together are called 2-2 composites. The ten basic connectivity patterns used in our work are illustrated in Figure 1. Many transducer properties can be improved by choosing the best connectivity pattern.

To reduce the acoustic impedance of the transducer, we embedded PZT fibers in a polymer matrix. This is a useful design for underwater sonar systems and for biomedical systems in which the impedance of the transducer must be matched to water or to human tissue. An additional advantage to the 1-3 design is the high sensitivity to weak hydrostatic pressure waves encountered in biomedical diagnosis and underseas operations.

The multilayer 2-2 composites with interleaved layers of piezoelectric ceramic and metal electrodes are made by a tape-casting process similar to that used in manufacturing capacitors. First introduced for adaptive optic systems in military satellites, these multilayer actuators are now used in printing systems and in the optical scanners used in supermarket check-out counters. These actuators are also under test for automotive and aircraft systems to remove unwanted vibrations.

Multilayer ceramic actuators are capable of generating large forces but the displacements are small and often shown sizable hysteresis. To remove hysteresis we replaced the piezoelectric PZT layers with electrostrictive PMN (lead magnesium niobate). This elminates the ferroelectric domains which cause hysteresis.

The second problem of small displacements have been solved by adding metal end caps to the ceramics. Under high voltage drive, the metal end caps undergo a binding motion which greatly enlarges the mechanical motion. These and other types of composite transducers (Figure 2) will be described at the meeting.

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ELECTRONIC/PHOTONIC MATERIALS

ERBIUM-DOPED OPTICAL FIBER AMPLIFIERS

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Optical amplifiers are revolutionizing telecommunications. For the first time, the full information carrying capacity of fiber optics can be unleashed. Optical amplifiers are the breakthrough which open the way for light transmission through optical fibers to increase one hundred fold or more. Thus, the information superhighway can take another step towards becoming the ideal that is depicted in the press.

As light passes through an optical fiber it is attenuated, so that its intensity must be periodically replenished. Until very recently, this was done by detecting the optical signal, converting it to an electrical signal, and then, in turn, using this signal to drive a new laser. This laser would launch the light signal along the next span of fiber, until the next regenerator station. The bandwidth, or information carrying capacity, of regenerator-based transmission systems is limited by the electronic components of the regenerators, which thus become bottlenecks for ultra high speed information transmission. The solution to remove these bottlenecks is to use optical amplifiers. Optical fiber amplifiers, by comparison, are purely optical in nature and require no high speed circuitry. The signal is not detected then regenerated, rather, it is very simply amplified in strength by several orders of magnitude as it traverses the amplifier without encountering any bottlenecks.

In an optical amplifier, an optical pump source provides energy to a specially chosen dopant ion directly embedded in an optical fiber. This dopant stores the energy until the signal traverses it. The signal triggers the release of this energy which directly amplifies the signal, by a factor of up to ten thousand. Electronic bandwidth limitations are removed as is the need for bulky and complex regenerators to amplify the light. To achieve this, erbium, the dopant element, must be added in a controlled way to the optical fiber. 1.5 microns is one of the wavelengths of light commonly used in long distance fiber optic transmission. When pumped at an appropriate wavelength, erbium emits light at 1.5 microns when a weak 1.5 micron signal triggers it (by stimulated emission). Fiber amplifiers were first proposed in 1964, during the first years of the laser, by E. Snitzer, then at the American Optical Corp. Key subsequent developments were the work of Payne, Reekie, Poole, and Mears at Southampton, who first showed that rate earth ions could be incorporated into a single mode fiber, and that of Desurvire, Simpson, and Becker, at AT&T Bell Laboratories, on traveling wave single mode fiber amplifiers doped with erbium.

Essential to the fabrication of optical amplifiers is critical control over the materials preparation of silica glass fiber doped with erbium. This achievement is based on a long series of accomplishments, which have resulted in the processes used by AT&T and Corning to make optical fiber. Erbium doping is a separate challenge due to the volatility of erbium compounds. This is due to the fact that the volatility of the erbium starting material is lower than that of the glass constituents of the fiber, making it harder to deliver erbium to the core of the fiber. Various solutions have been found, including high temperature vapor delivery, and also delivery by liquid forms of erbium compounds. It is also important, for an effective optical amplifier, to incorporate aluminum as well as erbium in the core of the fiber. Aluminum, which is not a usual constituent of optical fibers, aids in the fabrication of erbium doped fibers and also improves the performance of the amplifier itself.

Today's commercially available erbium-doped fiber amplifiers (commonly referred to as EDFA's) consist of a length of erbium doped fiber, typical 20 to 30 m long, one or two solid state laser pumps to excite the erbium ions so that they will provide gain, a fiber device that combines the pump and signal light and sends them both through the erbium fiber, and isolators to prevent feedback into the amplifier that would turn it into a laser rather than a single pass amplifier.

The first major implementation of these amplifiers is in long haul systems, such as the TAT-11 transoceanic fiber cable that AT&T and its European partners are installing across the Atlantic and which is due for completion in 1996. This cable, one of the first trans-oceanic cable to use fiber amplifiers,

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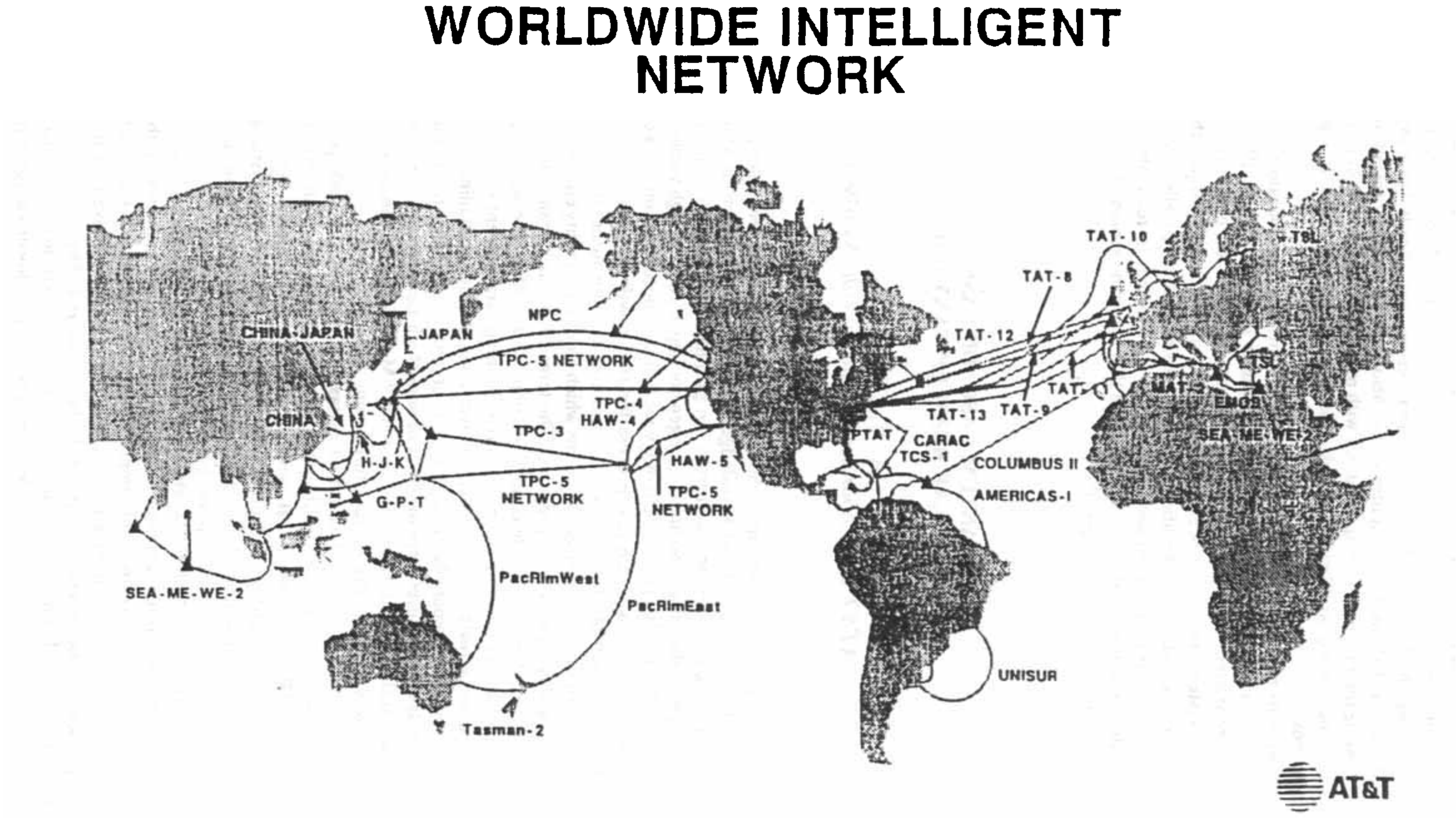

FIGURE 1 Worldwide intelligent network.

will provide a ten fold increase in voice and data transmission capacity over the previous trans-Atlantic cable. The amplifiers will be spaced every 33 km. A similar cable, TPC-5, is to be installed in the same time frame, linking the U.S. and Japan. A shorter version has already been installed between St. Thomas and Florida. Erbium fiber amplifiers have also been successfully tested in video distribution networks, showing their potential for applications with many end-users and short transmission distances. Figure 1 shows the existing worldwide network of long distance fiber cables. It is growing annually by leaps and bounds.

Scarcely four years passed from the first research demonstration of a laboratory erbium fiber amplifier in 1987 to its first introduction as a commercial product in 1991. Also in 1991, the first undersea experiments were started. By 1993, systems with lengths of 10,000 km had been demonstrated. More recently, longer system spans have been demonstrated with a novel technique, that of solitons. The rapid penetration of erbium fiber amplifiers into transmission systems parallels the surging interest and development in a global information superhighway. It is important to remember that without fundamental materials research and advances, such as those that led to the erbium fiber amplifier, such major technological advances would not be possible.

QUANTUM CASCADE LASER
MOLECULAR BEAM EPITAXY (MBE)

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When one applies knowledge from one technology to that of another technology, it often generates a third new technology. We combined knowledge of surface physics, such as atomic adsorption and desorption, with the knowledge obtained from ion propulsion engines for space travel, such as temperature controls, heat shieldings and liquid nitrogen cooling in an ultra-high vacuum, and applied them to crystal growth. This newly created technology we called molecular beam epitaxy (MBE).[1]

Molecular beam epitaxy is a thin film process for the growth of single crystalline semiconductor, metal, and insulator materials. It is a form of evaporation. It distinguishes itself from other evaporative methods as it incorporates ion propulsion concepts which allow high quality epitaxial layers with excellent electrical and optical properties to be prepared. The term "molecular beam" describes a unidirectional flow of molecules or atoms of the elements that comprise the film. The term "epitaxy" was derived from the greek words *epi* meaning upon, and *taxis* meaning arrangement or order. Epitaxy therefore describes the ordered growth of one crystalline layer upon another crystalline layer. A unique feature of MBE is the ability to prepare layers with atomic precision. The film grows atomic layer by atomic layer. These thin layer structures form the basis of many high-performance semiconductor devices such as high-speed integrated circuits, lasers, and detectors.[1] Most of the semiconductor lasers used in today's compact disc players are currently manufactured using MBE.[2]

Molecular beam epitaxy sets the standard for epitaxial growth and has made possible semiconductor structures that could not be fabricated with either naturally existing materials or by other crystal growth techniques. Since MBE can grow crystals with the precision of an atomic dimension, it opens a new field of functional devices utilizing quantum phenomenon. MBE led the crystal growth technologies when it prepared the first semiconductor quantum well and superlattice structures that exhibited unexpected and exciting electrical and optical properties.

Most recently, MBE fabricated the world's first unipolar semiconductor laser called the Quantum Cascade Laser.[3] This laser is fundamentally different from conventional lasers in that it can be tailored to emit light at a specific wavelength by simply varying the thickness of the structure using the same combination of semiconducting materials. This is in contrast to the conventional semiconductor laser which is dependent on the chemical nature of the layer material. The Quantum Cascade Laser is also different as it requires only one type of carrier (for example, electrons) rather than both electrons and holes. Light is emitted as the electrons drop from a higher to a lower energy state. MBE creates an "energy staircase" through the growth of a multi-layer, sandwich-like semiconductor structure. As the electrons drop down the "staircase" from layer to layer like water cascades down a multi-stepped waterfall, light is emitted at each step.

The building block of the active region of the laser is three $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ quantum wells. The quantum well widths (layer thicknesses) are 28, 35, and 8 Å (8 Å is about 3 atom layers). This building block is repeated 25 times (25 steps of the staircase) to enhance the light intensity. An electron micrograph of the active region of the quantum cascade laser is shown in Figure 1 (Figure not available). This type of laser operating at mid- to far-infrared wavelengths, has potential in a broad range of applications, such as environmental monitoring of air quality, industrial process control and free space point to point communications.

The Quantum Cascade Laser is dependent upon precision layer thickness to within an atomic dimension. It could not be made without the meticulous control of the layer structures possible with MBE.

The precision, control, flexibility and simplicity of MBE coupled with its ability for real-time growth monitoring makes MBE a powerful crystal growth technology. It is not only used in industrial research laboratories and universities throughout the world, it is also used in manufacturing because it is a high reproducible, high yield growth process.

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OXIDE SUPERCONDUCTORS

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Superconductivity was unknown until 1911 when it was discovered in mercury at extremely low temperatures (−450°F). Superconductors have numerous potential applications, but realizing this potential has been impeded by the low temperatures required for known materials to become superconducting. In the last few years, new materials have been discovered which become superconducting at considerably higher temperatures. These discoveries have revitalized interest in applications of superconductors.

Until the 1960's all known superconductors were metals or alloys. Oxides are known more as electrical insulators rather than conductors. It was, thus, considered surprising when I discovered[1] superconductivity in a barium-lead-bismuth oxide in 1975. Although the temperature required to produce superconductivity was still low (−435°F), this was considered to be a high-temperature superconductor at that time. In 1986, Bednorg and Müller discovered[2] superconductivity at an even higher temperature (−390°F) in a lanthanum-barium-copper oxide. This led to a flurry of research on copper oxide based superconductors. The structures of several of these were elucidated in my group at DuPont. Today, the temperature at which superconductivity can be achieved in copper oxide based materials has reached −225°F. We continue to explore new compositions and new synthesis approaches that might result in new materials which become superconducting at ever higher temperatures.

A multitude of applications can be envisioned for superconductors, and some of these have already been realized with the metallic superconductors. Superconductors can be used to advantage in the many aspects of electrical power, in its generation, transmission, transforming, storage and use in motors. Superconducting storage devices have been extensively evaluated and are becoming more broadly used. One of their advantages is that they can supply power essentially instantaneously in the case of short interruptions in power supply. Powerful magnets are made from superconducting wire, magnets such as those used in Magnetic Resonance Imaging (MRI) and to levitate trains. Superconductors give us our most sensitive detectors of magnetic fields and are, thus, used to detect brain waves.

The oxide superconductors are just beginning to be developed into useful products. Impressive wire has been produced from the oxide superconductor, but to date, superior properties are only present in lengths of a few feet. Prototype electronic devices have been fabricated from the oxide superconductors by several different companies. When fully developed, these devices promise to give us faster computers as well as better communication, radar and MRI.

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METALS

NEODYMIUM IRON BORON (Nd-Fe-B) PERMANENT MAGNETS

JOHN CROAT
Magnequench

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DISCOVERY

Permanent magnets have long occupied an important position in technology. Among the multitude of products using permanent magnets are television, telephones, computers, videocassette recorders, cameras and perhaps surprisingly to many consumers, automobiles. In fact, automobiles are by far the largest users of permanent magnets. Applications include, e.g. the starter, blower motor, windshield wipers, window lift, seat adjust and fuel pump motors. A fully modern automobile can have more than 40 d.c. accessory motors as well as various sensors and gauges, all of which use permanent magnets.

In the late 1970's, largely in response to rapidly increasing gasoline prices and the need for lighter weight, smaller vehicles, a team of researchers at the General Motors Research Laboratories began investigating possible high performance alternatives to the relatively low performance ferrite magnets currently used in automobiles. The materials that this group focused their effort on were a combination of the so-called light rare earths (lanthanum, cerium, praseodymium and neodymium) with iron. These four rare earth elements were chosen because their relatively high abundance made them the most attractive economically. The possibility of producing permanent magnets from these materials with iron had been discussed for several decades. Development was severely hampered, however, by the lack of suitable compounds, which are a quintessential ingredient for conventional permanent magnets. One approach that the General Motors team investigated for surmounting this obstacle was to employ rapid solidification techniques to form non-equilibrium or metastable microstructures. This line of research led to the discovery of neodymium-iron-boron alloys and to the identification of the novel ternary compound, $Nd_2Fe_{14}B$, responsible for their intrinsic magnetic properties.

Although a comparatively recent discovery, neodymium-iron-boron permanent magnets have already had a major technological impact on both the users and manufacturers of magnetic materials. Magnetic energy levels in production now exceed those of the corresponding ferrite grades by a factor of ten. This, coupled with the relatively low cost of these materials, has made neodymium-iron-boron magnets the fastest growing class of permanent magnet materials heretofore developed.

COMMERCIALIZATION

General Motors commercialized this material at Delco Remy, one of its electrical component divisions, in Anderson, Indiana. The business unit was named MAGNEQUENCH and a modern 160,000 $ft.^2$ plant was completed and occupied in 1986. The plant includes a high tech foundry, a manufacturing area and an engineering/administration building. The business has been growing at roughly 35%/year for the last five years and now employs 275 people.

The manufacturing process begins with the production of a high grade Nd-Fe-B alloy. This alloy is then rapidly solidified by a melt-spinning process, a technique in which a thin stream of molten alloy is directed onto the outer surface of a water-cooled disk; cooling rates are estimated to be as high as 500,000°C/sec. This process quenches in the extremely fine microstructures responsible for the permanent magnet properties of this material.

The flake-like material produced by this melt-spinning process is crushed into a powder that is sold directly to a large base of magnet producers worldwide or is used to produce various grades of magnets internally. Two general categories of magnets are produced. The first are bonded magnets, which are an essential feature of many high-tech products. These bonded magnets are manufactured by blending the powder with an organic binder and then pressing or molding into the desired shape. The second category are fully dense metallic magnets which are produced by hot pressing or hot forging the powder into the desired shape. Both categories of magnets have their own wide and often unique base of applications worldwide.

PRODUCT APPLICATION

Neodymium magnets can potentially be used wherever a permanent magnet is required. Most of the early success of neodymium magnets has been in high technology fields such as computer disk drives, office automation and consumer electronics. Most of the products in these sectors utilize brushless motors. These motors use rotating magnets and require lower inertia for quicker and more accurate response. Also, these high technology industry sectors are normally pushing the envelope of performance. Because of this, neodymium has become the magnet material selected by most of these products.

Computers continue to require increased capacity, faster access time and smaller disk drives. Virtually all the spindle motors in computers utilize neodymium magnets today. Office automation also utilizes the high performance of neodymium magnets in a variety of motors for fax machines, printers, typewriters and copy machines. Consumer electronics is another area where neodymium magnets play an important role. Size, performance and convenience require more power in a smaller package in several current products including cameras, video recorders, camcorders, tape recorders and CD players.

The appliance sector, including power tools, is predicted to be one of the next growth areas for neodymium. Some industry studies predict that by the year 2000, 80% of all power tools will be cordless. This translates into rapid growth for permanent magnet motors with neodymium designed into the high end applications. Appliances, such as washing machines, heating and air conditioning and refrigerators are being targeted for major efficiency improvements.

FUTURE

According to both historical market trends and future market demand indicators, the neodymium-iron-boron market is well positioned for continued rapid growth. Today, sales in the neodymium-iron-boron market total approximately $500 million. However, forecasted growth indicates that the market will have sales of nearly $2.7 billion by the year 2000. Growth will continue in computers, office automation and appliances. Clearly, automotive applications represent a large opportunity for future growth of neodymium-iron-boron magnets. As safety, efficiency and convenience continue to drive the automobile designs, neodymium offers the designer a high energy magnet at a reasonable cost.

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AERMET® 100 ALLOY—A NEW ULTRAHIGH-STRENGTH STEEL DESIGNED TO SOLVE PRACTICAL PROBLEMS

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Steel is still one of the most widely used materials for structural applications. As the strength of a given steel increases, a component made from that steel can withstand higher loads prior to failure. However, there are a number of limiting factors that place a practical upper limit on the strength of a given component. Two of these have to do with the actual steel used to manufacture that component.

The first limiting factor is the attainable strength of the steel itself. Steels are available in greatly varying strength levels for different applications. However, service failures have shown that there is a limit to the benefit of increased strength alone. Although a steel may be strong, there can still be the danger of catastrophic brittle failure. This leads to the second limiting factor, which is the toughness of the steel. The major problem faced by ultrahigh-strength steels, i.e. those with strength exceeding 250 ksi, is to be able to resist failure even in the presence of a crack. One goal of steel manufacturers over the decades has been to produce an ultrahigh-strength steel with improved fracture toughness.

Efforts were undertaken in the Carpenter Technology Corporation R&D laboratory to develop an ultrahigh-strength steel with a combination of strength and fracture toughness better than that of any other available structural material. After extensive literature searches, the most promising alloy system was chosen for further experimentation. Numerous 17-lb. heats were melted and processed in the R&D laboratory, and properties were evaluated. Based on these small heat results, mathematical computer models were written that predicted mechanical properties based on composition. Based on the results of these computer models, a smaller number of 400-lb. laboratory heats were melted and evaluated. A single composition was then chosen for scale-up to a full-size (15,000 lb.) production heat. However, the research effort did not stop there, as a considerable amount of process research was required in order to be able to consistently manufacture a commercial product with the desired properties.

The resultant composition determined by this research work was that of AerMet® 100 alloy. AerMet 100 alloy is recognized as having the highest combination of strength and fracture toughness of any currently available steel, a U.S. patent[1] having been granted. AerMet 100 alloy is commercially available and its unique combination of strength and fracture toughness has met a number of specifications.[2,3] The list of commercial applications for AerMet 100 alloy is growing rapidly.

Major sales for the alloy to date have been for landing gear for new carrier-based military aircraft. The specifications for these landing gear require an alloy capable of 280 ksi ultimate tensile strength combined with a fracture toughness of 100 ksi$\sqrt{\text{in.}}$, which only AerMet 100 alloy is capable of achieving. The use of this alloy for this application should make the landing gear significantly safer, with far less chance of gear failure due to undetected flaws compared to the alloy previously used.

Other aerospace applications have included critical components of the braking system of a large commercial aircraft. If an emergency arises and takeoff must be aborted, a great deal of energy is transferred to the brakes, causing brake temperature to rise significantly. The alloy previously used for this application can tolerate temperatures only up to 500°F, whereas AerMet 100 alloy will be able to tolerate braking temperatures well in excess of 500°F.

This new steel has also shown excellent properties as an armor material, especially where weight is a primary concern. AerMet 100 alloy has been specified for critical ballistically tolerant components in a military helicopter. Additionally, police forces are testing it for personal protective gear and riot shielding, as this alloy is the only material capable of stopping both a 9 mm projectile and a knife thrust within the given weight restrictions.

Civilian markets include the use of AerMet 100 alloy for tooling applications. The substitution of this new alloy for existing alloys has resulted in up to tenfold increases in the life of tooling, which should allow consumer goods to be produced at a lower cost. Additionally, many complex parts for consumer goods are currently produced from conventional alloys by using expensive machining processes. The use of AerMet 100 alloy, with its greater combination of strength and toughness, would allow these parts to be produced by a much less expensive process, casting of near-net shape parts. AerMet 100 alloy has also been made into tubing for bicycle frames. This new alloy has one of the highest strength to weight ratios of any metallic material, allowing the production of extremely strong and light frames for racing bicycles.

AerMet 100 alloy is currently at the leading edge of steel technology. This steel will allow many parts to be made stronger and lighter than ever before. AerMet 100 alloy may be the new stepping stone to even greater advances in steels, with future advances producing properties never before considered possible.

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AMORPHOUS ALLOYS FOR HIGH FREQUENCY SWITCHING POWER SUPPLIES

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INTRODUCTION

Since the superior soft magnetic properties of amorphous alloys were discovered in 1974,[1] a number of research efforts have been conducted related to their magnetic properties and practical applications such as magnetic heads, magnetic sensors and switching power supplies (SPS). We have developed amorphous alloy cores for high frequency SPS which have been in great demand for computers and other equipment and systems.

In this article, we describe the developed amorphous alloy cores for use in high-frequency SPS.

AMORPHOUS ALLOYS FOR SPS

One method of stabilizing the output of SPS relies on use of magnetic amplifiers, for which we developed amorphous alloys to be used. The magnetic properties required for magnetic amplifiers include as square a magnetization curve as possible and low coercive force at the operating frequency, and good thermal and mechanical stability.

We have developed Co-based amorphous alloys covering the above mentioned requirements. They are made of Co-Fe-Nb-Si-B and have zero-magnetostriction. Nb addition is crucial in improvement of magnetic properties and thermal stability.[2,3] The control of amorphous alloy tape thickness is also very important; thinner is better for low core loss at higher frequency. (Figures not available) Figure 1 shows squareness of magnetization curve and coercive force as a function of the tape thickness for a developed amorphous alloy core. Thinner thickness leads to lower coercive force with keeping the squareness, thus lower core loss at higher frequency, demonstrating the possible operation at higher frequency for SPS. Tape thickness obtained by the conventional melt quenching process is above about 20 μm, and it is very difficult to make the thinner tapes. We have succeeded, however, to make 5 μm thick amorphous tapes,[4] by melt quenching in vacuum, as shown in Figure 2.

APPLICATIONS TO SPS

Figures 3 and 4 exhibit amorphous alloy cores developed and SPS operating at 80 kHz and 500 kHz using the amorphous cores, respectively. These demonstrate that the operation at higher frequency reduces the dimensions of the SPS and the cores. We have also succeeded to make a 1 MHz SPS using the 5 μm thick amorphous alloy tapes. Aging of SPS adopting the amorphous core disclosed high thermal stability.

We have developed other amorphous alloy cores such as ones used to suppress the transient current (spike current), choke coils for SPS and cut cores for high power inverter-type power supplies, the two latter of which are made of Fe-based amorphous alloys.

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SINGLE CRYSTAL TURBINE AIRFOILS

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PCC Airfoils

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The performance of gas turbines is directly related to the turbine inlet temperature. Increases in this temperature through improvements in material selection, special casting processes and cooling schemes have resulted in the continuous and significant increase in the efficiency and effectiveness of the jet engine.

The ability to economically produce single crystal turbine airfoils in production quantities is an important processing contribution that has allowed the turbine temperatures to be significantly increased and has helped sustain the aerospace industry in the United States as a world leader.

The purpose of this presentation is to summarize the development efforts that have led to the use of single crystal technology in turbine engines. These efforts are the result of programs from a number of companies in the industry, which include engine manufacturers, alloy producers and airfoil casters.[1-3]

Turbine airfoil materials are cast from nickel-base superalloys, which contain a variety of alloying elements that are added to enhance oxidation resistance and produce both precipitation and solid solution strengthening. The alloys are unique in their ability to maintain relatively high strength at temperatures approaching 90% of their melting point. The initial application of superalloys to cast airfoils depended on conventional investment vacuum casting techniques, which allowed near net shape parts to be produced with relatively complex internal cooling passages. The nickel-base alloys, which have a face-centered cubic structure can be cast under controlled solidification conditions so that a particular direction of the structure is aligned parallel to the length of the airfoil. Under conditions where a grain selector is used (either a seed or a geometrical ramp) the airfoil can be cast as a single crystal.

By optimizing the composition of the alloys and the casting and heat treatment parameters these single crystal components exhibit improvements in creep strength and thermal fatigue resistance that are approximately 9× greater than conventionally cast equiaxed turbine blades and 2 to 3× greater than directionally solidified airfoils with aligned grain boundaries. The single crystal components can be placed in the hot section of a turbine engine.

The research and development contributions that have allowed the single crystal technology to be directly applied to production components are:

- *Alloy Development*—Grain boundary strengtheners that depress the melting point can be eliminated allowing higher heat treat and use temperatures. More recently additions of rhenium have further enhanced the high temperature capability of the single crystal alloys.
- *Ceramic Strength*—The ceramics used for molds and for ceramic cores are designed both compositionally and geometrically to maintain very accurate dimensional tolerances at temperatures of several hours above the melting point of the alloys (approximately 2700°–2800°F).
- *Furnace Design*—Vacuum furnaces have been designed that provide very accurate process control during casting. The furnaces allow the mold to be maintained above the melting point of the alloy and then withdrawn at a controlled rate using a variety of baffles and chill plate designs to maintain high gradients during the casting process. The designs, which allow a relatively large number of complex parts (typically 10–25 parts) to be cast during a single pour, represent the factor that greatly contributes to the cost effectiveness of the process.
- *Process Parameters*—The proper use of grain selectors, feeders, casting parameters and filters to produce cast airfoils that meet the very stringent quality requirements required for engine performance represent a significant contribution to the successful application of single crystal technology. In addition the definition of heat treatment parameters and controls to allow proper strengthening is also a significant and necessary contribution.
- *Solidification Modeling*—Appropriate modeling of the single crystal casting process has provided a better understanding of the critical casting parameters and contributed to the acceleration of process definition and control.

As a result of these development efforts, single crystal technology is used on virtually all the latest military and commercial high pressure turbine airfoils with over two million single crystal airfoils being produced thus far. In aircraft applications the future will involve the use of more complex thin-wall cooling schemes coupled with single crystal processing. Also the rapidly growing land base turbine market will use single crystal parts with the significant challenge being the scale-up of the processing methods to very large airfoil geometries.

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