MATERIALS
METALS:
- aluminum monocoques
- aluminum honeycomb
- ball hammered aluminum
- hydro-formed aluminum
- super-formed titanium
- drag-formed titanium
- magnesium casting
- the finger

PLASTICS:
- composite hulls
- inflatable panels
- hardened ropes
- roto-molded plastic
- pressure-formed plastic
- pulltrusion composites
- rigid sails

GLASS:
- slumped glass

MASONRY:
- ceramics
- lightweight concrete
Aluminum Monocoque

Full and semi-monocoque
Component and Connection Characteristics

Adhesive bonding:
superior stiffness and fatigue characteristics, best used in combination with welds or rivets for resistance against large deformations

Self-piercing rivets:
can be automated, and results in higher fatigue strength

Spot welding:
traditional joining technique for steel monocoques, but relatively low fatigue strength due to thermal distortion of metal

Laser or MIG welding:
used where only one side of the workpieces can be accessed or where a continuous joint is required

Sheet forming:
uses components for both structural and space-enclosing functions, rapid assembly

Extrusion:
high stiffness to weight ratio, high accuracy in assembly due to absence of welds

Casting:
mainly used for structural parts and engine parts

Semi-monocoque Variations:
separate monocoque assemblies are individually constructed to meet different specifications, then bolted together to form the complete monocoque frame

structural division of assemblies

thermal division of assemblies

no division of assemblies

Tribology: concerns pertaining to the tool/sheet interface

Sheet Forming

Tooling

Methods

Noise tolerance

R = 2t

Sheet composition

aluminum sheet

aluminum skins w/ balsa wood core

aluminum or polymer matrix composit skin with aluminum honeycomb core

Extrusion

Straight extrusion

Bent Extrusion

Hydroformed Extrusion

Die Casting

Low-pressure die-casting system

Low pressure die casting

High pressure die casting
Aluminum Monocoque

Development and Overview

Tubular Space Frame
Components:
Circular or square section tubes
Connections:
Welded
Example:
Lamborghini Countach, Diablo

Steel Monocoque Frame
Components:
Stamped steel sheets
Connections:
Spot weld, fillet weld
Example:
Volvo, Mercedes

Aluminum Monocoque Frame
Components:
Stamped sheets, straight and bent extrusions, injection castings, hydroformed extrusions
Connections:
laser weld, spot weld, hybrid laser/MIG weld, self-piercing rivets, structural adhesives, rivet bond, spot clinching
Example:
Audi A8, Jaguar XJ, Aston Martin Vanquish

On Average:
40% lighter than equivalent steel frame
60% stiffer

Trek Downhill

Ninja Motorcycle

Audi A2
Monocoque space frame

laser welds         mig welds
VACUUM CASTINGS     STAMPED SHEETS
spot welds          hybrid laser/mig welds
DIE CASTINGS
BODY

CHASSIS
HYDROFORMED EXTRUSIONS
rivet bonding
self-piercing rivets

SYSTEM MOUNTS
BENT EXTRUSIONS
heat-cured epoxy adhesives

FRAME
STRAIGHT EXTRUSIONS
spot clinching

Ben K. Mickus
Aluminum Monocoque

Variable Component Assemblies

**Audi A8 Space Frame**
Patented monocoque system

**Description:**
Number of parts: 260
Weight: 475 lbs

**Joining Methods:**
Self-piercing rivets: 2400
MIG welds: 64 meters
Laser welds: 20 meters
Laser hybrid welds: 5 meters
Spot clinching and Structural adhesives

**Component Parts:**
Extrusions: 59 (22%)
Castings: 31 (14%)
Stampings: 170 (64%)

---

**Aston Martin Vanquish**
Extrusion Intensive Monocoque

**Description:**
Number of parts: 80
Weight: 319 lbs

**Joining Methods:**
Self-piercing rivets: 252
MIG welds: none
Laser welds: none
Struct. adhesives: 3 m²

**Component Parts:**
Extrusions: 40 (50%)
Castings: 0
Formed Sheets: 40 (50%)

---

**Jaguar XJ**
Primarily Stamped Sheet Monocoque

**Description:**
Number of parts: 310
Weight: 650 lbs

**Joining Methods:**
Self-piercing rivets: 3195
Blind rivets: 22
MIG welds: 2 m
Spot clinches: 110
Struct. adhesives: 114 m

**Component Parts:**
Extrusions: 22 (7%)
Castings: 15 (5%)
Formed Sheets: 273 (88%)
Aluminum Monocoque

Possibilities and new directions

Electromagnetic Forming of Aluminum

Optimized method for shaping aluminum sheets into panels

- Improved forming limits with minimized springback of traditional stamp forming
- High velocity forming allows for rapid production cycle times
- Improved tribology with only one fixed tool, and no moveable tool needed.
- Reduced need for lubricants and cleaning agents of stamping processes
- Focus on production of non-axisymmetric shapes from flat panels
PAMG-XR1 5052 aluminum honeycomb is a lightweight core material which offers superior strength and corrosion resistance over Commercial grade aluminum core. PAMG-XR1 5052 core is made from 5052 aluminum alloy foil and meets all the requirements of MIL-C-7438.

- Elevated Use Temperatures
- High Thermal Conductivity
- Flame Resistant
- Excellent Moisture and Corrosion Resistance
- Fungi Resistant
- Low Weight / High Strength

PAMG-XR1 5052 honeycomb is available in four forms: unexpanded blocks, unexpanded block slices, untrimmed expanded sheets and cut to size expanded sheets. PAMG-XR1 5052 core is also available with or without cell perforations to facilitate cell venting for certain applications.

Sheet Length (W): 150" maximum typically
Sheet Width (L): 60" maximum typically
Tolerances:
Length: 0", +6"
Width: 0", +6"
Thickness: + -0.005", + - 0.001" Available
Density: + - 10%

Thickness: 1/2", 3/4", and 1"
Widths: 4' & 5'
Lengths: 8', 12'

** cockpit seat=aluminum honeycomb **
<table>
<thead>
<tr>
<th>Honeycomb Designation</th>
<th>Bare Compression Density (PCF)</th>
<th>Strength (PSI)</th>
<th>Plate Shear Modulus (KSI)</th>
<th>Plate Shear Strength (PSI)</th>
<th>L” Direction</th>
<th>“W” Direction</th>
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<td>Cell Size</td>
<td>Foil Gauge</td>
<td>Density (PCF)</td>
<td>Strength (PSI)</td>
<td>Modulus (KSI)</td>
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aluminum honeycomb panels

honeycomb component
Temperature usage up to 175 °C
High Thermal Conductivity
Flame resistance
Moisture and Corrosion Resistance
Fungi Resistant
High Strength
Low weight
The expanded core is bonded to the outer facings with a two pack adhesive, its properties allow it to "wick" on to the core cell walls to ensure large area of contact. The adhesive is applied on a dedicated computer controlled spray booth facility, which allows close monitoring of coat weights and accurate application to all substrates.

During this stage any inserts or conduits can be included within the core to allow site fixing or wiring of ancillary fittings to concealed points. Panels can have structural frames incorporated in the same manner to agreed configuration.

The sandwich faces and core are laid up and accurately aligned prior to transferring by means of roller table to the press.

The final bonding process is carried out in a heated hydraulically controlled press to ensure uniformity of each panel. The panel remains in the press during the adhesive curing process, this is closely controlled taking account of press and ambient temperatures to ensure reliability of bond.

After the curing process has been completed the panels are removed from the press, inspected and stacked with appropriate interleaving prior to transfer to Packing and Despatch area.

The Aluminium Honeycomb panels will be wrapped and strapped suitable for mechanical handling and where required crated suitable for onward freight. The specifications for the protection and marking will be as agreed with individual clients.
Shot Peen Formed Aluminum

ALUMINUM / PEENING

Aluminum: General
A light, nontoxic (as the metal), nonmagnetic and nonsparking metal which is easily machined, formed, or cast. Aluminum is an abundant element in the earth's crust, but it is not found free in nature, and must be extracted from bauxite, an aluminum ore.

Alloys
Alloys include Copper, Manganese, Silicon, Magnesium, and Zinc, among some other elements.

Welding
While it is a useful material in construction, it is difficult to weld due to its high thermal conductivity, high thermal expansion coefficient, and low melting temperature among other reasons. Laser welding is one welding option, and development is currently underway to refine this process as well as make it suitable for on-site use.

Shot Peening: A precisely computer-controlled cold-working process in which the surface of a metal part is bombarded with thousands of small spherical media (shot), usually made of steel, but can also be made of glass or ceramic. Each shot creates a small dimple in the surface of the material causing plastic deformation of the material. The outer layer of the material yields in tension, while the layers just beneath the surface attempt to restore the part's original shape, thereby creating a zone in compression. Overlapping dimples create a uniform layer of compressive stress in the metal.

Benefits:
• Cracks will not initiate nor propagate in a compressively stressed zone
• Significant increase in part life
• Increase in surface hardness
• Increasing resistance to fatigue failures, corrosion fatigue, stress corrosion cracking, and closing of surface porosity
Shot Peen Formed Aluminum

FORMING

**Shot Peen Forming:**
A computer-controlled cold-working process derived from shot peening which stretches material to impart variable compressive stresses in the panel surface, resulting in the ability to form complex compound curvatures without form tooling. This process is best suited for forming large panels where the bend radii are reasonably large, however ‘fixtures’ can be utilized to accommodate more severe forms. A newer development utilizes two robots able to produce double-sided shot peening. Once forming is complete, the part is trimmed to exact size requirements. The part will then be rinsed in a chemical bath to clean off any steel or iron residue.

**Benefits:**
- Dieless process, resulting in reduced costs and manufacturing time
- Larger parts resulting in less on-site assembly
- Increased resistance to flexural bending
- Long-term retention of complex shapes
- Tight tolerances
FORMING

Process: Peen forming is very similar to other cnc processes. Curved forms are designed using various modeling software packages, and then subdivided into a series of panels dependent of chosen facility size and equipment. The curved panels are translated into a series of tool paths using company-specific software, coupled with shot size, and then sent to the cnc machine. The metal panels which will become the material for peening are stamped based on required size and shape. This stamping is not necessarily flat, but can also include some shaping of the material as well as forming stiffeners along the surface. The metal panels are then loaded into the cnc machine and bombarded with shot fired from air-powered nozzles which do not glide along the surface uniformly, but rather vary their speed dependent on form and required material thickness.
COMPANIES - WORLDWIDE

**NMF Group**
- **Location(s):** Quebec, Canada / Wichita, KS USA / Zaragoza, Spain
- **Facility:** World’s largest computer-controlled shot peen forming machine
  - Formax® system
- **Capacity:** 110' long x 12' wide
- **Clients:** Bombardier Aerospace, I.A.I. / General Dynamics, Embraer / Gamesa

**Metal Improvement Company (MIC)**
- **Location(s):** AZ, CA, CT, FL, IL, IN, KS, LA, MA, MI, MN, NY, NC, OH, PA, TX, WI USA / Canada / England / Sweden / France / Germany / Belgium / Italy
- **Facility:** Peenmatic Machinery®
  - Variety of other services
  - Approvals in a variety of fields
- **Capacity:** 100' long x 10' wide
- **Clients:** Aerospace, automotive, chemical, marine, agricultural, mining and medical industries

**Kugelstrahlzentrum (Out of Business?)**
- **Location(s):** Aachen, Germany
- **Facility:**
  - Double 7-axes CNC peening machines
  - Integrated 3D-contour measurement device
  - Compression Forging Process
- **Capacity:** 6000 x 3000 x 1500 mm (19.7' x 9.8' x 4.9')
- **Clients:** Airbus, Airane
Hydroforming means pushing a piece against a rigid die by applying a large pressure through a deformable medium, liquid or polymer. Large volume changes are achieved with the former and the latter allows to solve easily tightness problems.

Fluid pressure within the tube is increased after the die closes to force the material into the deformation zone. During this process, axial feeding and internal pressure are controlled simultaneously to improve the process's material-shaping capabilities.

When hydroforming extruded aluminum profiles, stretching a tube's cross section beyond its yield point (2 to 3 percent elongation) is required to prevent springback and achieve tight tolerances. Having flanges and webs in the extruded tube makes the die geometry and sealing more complicated. In many cases, a large amount of axial feeding is not possible.

If the equipment is expensive, on the other hand reproducible parts are obtained straightforward. Therefore, it is attractive to hydroform a material with a large ultimate elongation.

Computer simulation of the hydroforming process should be used to evaluate the limits of deformation.
Overall the new A8 body requires considerably less joining effort than its predecessor because Audi’s experience with aluminium has increased over the last decade. For example the vehicle has a single-piece side-panel. The 3.45m pressing weighs less than 7kg and replaces the eight unique components of the previous model. In total the number of components on the ASF has been reduced from 334 to 267. This is achieved through the use of large-format panels such as the side panel, extruded sections such as the 3m long hydroformed roof frame and multifunctional large castings such as for the radiator tank.

**HISTORY**

The first major application of hydroforming came in 1990, when it was used by Chrysler in the US to make the instrument panel beam for their minivan platform. Ford USA adopted the technique for engine cradles in 1994, and by last year 3.2 million components were hydroformed using the Vari-Form process.

**ENVIRONMENT**

Weight plays a big role in automotive and aerospace industries. At the same time, the demand for lightweight workpieces in vehicle construction such as space frames of steel and aluminium as well as chassis components, propelled hydroforming to the forefront of automotive manufacturing. The process is also applied in the exhaust gas system industry.

**ALUMINIUM**

Has emerged as a feasible material for hydroformed auto parts. It is predicted to make inroads into what was once considered the territory of carbon and stainless steel. This light-weight metal has gained widespread usage in the automotive industry as it reduces overall vehicle weight, leading to enhanced fuel efficiency.

**HYDROFORMING**

Has brought about the reduction of weight, costs, and number of parts per vehicle. Tube hydroforming has found many structural applications in cars and trucks. These include engine cradles, radiator supports, frame rails and cross members, instrument panel beams and exhaust system components.

**LAND ROVER**

Corus collaborated with Land Rover in a programme to demonstrate a hydroform-intensive body structure. Hydroformed versions of body-in-white components for the Freelander vehicle were designed and evaluated, and 1200 individual components were produced on a variety of hydroforming machines. This quantity was large enough to evaluate process consistency, and typical examples were used to build eight body frames and three running vehicles.

**ULSAB (Ultra Light Steel AutoBody)**

This study underlines the reason for the interest in body structure hydroforming. The rail connecting the A and B pillars and the C pillar with the rear strut mount is a single hydroformed component, typically replacing up to eight press-formed components and eliminating sub-assembly: the result is a lightweight component that is structurally much more efficient than the conventionally structured rail.
Hydroformed Aluminium

OTHER INDUSTRIES USING HYDROFORMING

>AEROSPACE

The concept of hydroforming has been in regular use in the aerospace industry with continued success. Clark Manufacturing's aerospace sheet metal forming house has been hydroforming aluminium components since the 1970s. The majority of the business is with the Boeing divisions, with hydroformed parts on every plane they make, and also Lockheed Martin, in New Orleans, on the Space Shuttle External Tank program.

BIKING INDUSTRY

Biometric light hydroformed Aluminium 7005

KX125 - The new 48mm inverted fork and rear suspension – now with a hydroformed aluminium swingarm – are fully tunable and even more responsive.

INDUSTRIAL LIGHTING

Anodized finnish on hydroformed aluminium faceted reflector

MACHINERY

The main functions of a hydroforming press are to open and close the die, provide clamping load during the forming process to eliminate elastic deflections, and die separation. Additional units that are required to carry out the process include axial force cylinders and a pressure intensifier.

Currently, hydraulic presses are used to provide large clamping forces during the process. These presses are usually very expensive. However, several low-cost equipment designs with separate actions for opening/closing the tooling and providing the clamping load are being developed by press companies.

The number of tube hydroforming applications will increase by better understanding of materials and the process. In many cases, reliable computer simulations will help in developing more robust hydroforming techniques. Selection of proper materials and lubricants is critical for the success of the process. Advanced materials and lubricants are being developed in various research institutes and companies.

CANADA

is undoubtedly one of the largest centres for tube hydroforming technology. Some notable Canadian firms active in advancing hydroforming technology world-wide include Dofasco Inc, a Hamilton, Ontario-based steel maker that has two steel tube mills in Canada dedicated solely to hydroforming. Novamerican Steel Inc. of Montreal, Quebec also is very active in hydroforming. Novamerican started out by supplying tubes for Magna International Inc. of Aurora, Ont. when it began using the process to make engine cradles for then Chrysler Corp.
Hydroformed Aluminium

ADVANTAGES AND DRAWBACKS OF HYDROFORMING

ADVANTAGES
> COST EFFECTIVE Viable alternative to conventional matched die stamping, especially for cost-sensitive parts with irregular contours
> WEIGHT REDUCTION
> IMPROVED STRUCTURAL STRENGTH AND STIFFNESS compared to stamped or welded assemblies.
> SIMPLE AND LOW COST TOOLING as a result of fewer parts.
> SIMPLIFIED ASSEMBLY fewer secondary operations.
> FORM COMPLEX SHAPES AND CONTOURS. ability to process more complex components in a single operation.
> DIMENSIONAL PRECISION Tight dimensional tolerances and low springback.
> ECONOMY OF MATERIAL The process expands a smaller tube into a larger size, allows 50% expansion in localized areas
> REDUCED SCRAP
> DESIGN TO PRODUCTION TIME SAVING
> EASE OF DESIGN CHANGE
> NO PART LIMITATION SIZE
> MATERIAL VERSATILITY
> MINIMAL OR EVEN NO CNC PRE-BENDING

DRAWBACKS
> SLOW CYCLE TIME
> EXPENSIVE EQUIPMENT
> LACK OF EXTENSIVE KNOWLEDGE BASE FOR PROCESS AND TOOL DESIGN

The feasibility of hydroforming has to be investigated from both an economic and mechanical standpoint for each individual part. To reduce cycle times, secondary operations, such as piercing, need to be integrated with the hydroforming process. Computer simulation of the hydroforming process also can and should be used to evaluate the limits of deformation.

LARGE EXPANSION

Because of material hardening during the bending and preforming of the tube before it is hydroformed, material properties change, and some of the tube's formability is already used up. Therefore, to achieve large expansions during hydroforming, either an intermediate annealing step is required, or a material with high ductility should be selected.

However, because the ductility of aluminum alloys is limited when compared to steel's, most hydroformed parts made with aluminum alloys are limited to calibration to achieve tight dimensional tolerances after bending.

WEB LINKS

www.tubehydroforming.com
www.hydroforming.net
www.thefabricator.com/xp/Fabricator/Articles/Experts/Article111/Article111_p1.xml
www.advancedmanufacturing.com
www.advancedmanufacturing.com/November01/techreport.htm
www.motionnet.com
imx.epfl.ch
www.kaupp.com/hydro.htm
Stretch forming has been used on titanium mainly to contour angles, hat sections, Z-sections and channels, and also to form skins to specification-contours. Stretch Forming is a time proven process used to form close tolerance shapes for the Aerospace, Military and Commercial industries. This process allows us to create or duplicate any radii, complex contour or form using extruded shapes of varying profiles, flat sheets, square, rectangular, round or channel shapes, "I" beams or brake form shapes and offers the desired repeatability of shape from part to part.
Stretch Draw Forming is a process which combines the two processes of Stretch Forming and Draw or Deep Draw Forming with excellent results involving the forming of complex or reverse contours. The implementation of this technique is replacing the outdated process of Drop Hammer forming. The Stretch/Draw Form process is cleaner, quieter, more accurate and efficient and eliminates environmental concerns by removing Lead By-Products associated with the Drop Hammer process.
Stretch forming is attained by gripping the section to be formed in knurled jaws, loading until plastic deformation begins and then wrapping the part around a male die. Loading of the part or sheet until plastic deformation begins and wrapping around the die should be done at a slow rate. Spring back of most titanium alloy is equivalent to that of ¼ to ½-hard 18-8 stainless steel.

Types of machines:

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<tr>
<th>Machine Type</th>
<th>Details</th>
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<td>Stretch Form</td>
<td>Stretch Form, Stretch Draw, Wipe Form, Joggle And Ring Roll Equipment</td>
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<td>Erco Skin Stretch Press</td>
<td>725 Ton, Material Size 14' x 18', Model 1280</td>
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<td>Sheridan Gray Extrusion Stretch Press</td>
<td>300 Ton, 38' Finished Part Length, Individual Arm</td>
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<td>Stretch Press-Hydratex</td>
<td>150 Ton, Individually Actuated Arms - 25' Between Cylinders (K&amp;T Type Model A-14)</td>
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</tr>
<tr>
<td>Stretch Press-Hydratex</td>
<td>20 Ton, Individually Actuated Arms - 14' Between Tension Cylinders (Hufford Model A-7 Type)</td>
</tr>
<tr>
<td>(2) Hufford A-5 Stretch Press</td>
<td>12.5 Ton, 14' Finished Part Length (With Extensions)</td>
</tr>
<tr>
<td>Cyril Bath Radial Draw Former</td>
<td>25 Ton, 8'4&quot; Diameter With Wiper Attachment</td>
</tr>
<tr>
<td>Cyril Bath Press</td>
<td>10 Ton, 36&quot; Diameter Table With Transverse Wiper Attachment</td>
</tr>
<tr>
<td>270 Ton Horizontal Four Way Sheet Stretch Draw Press</td>
<td>30' Finished Part Length, With 72&quot; Articulating Jaws</td>
</tr>
<tr>
<td>Pines 3/4&quot; Bender</td>
<td>6 Station Automatic Angle</td>
</tr>
<tr>
<td>Pyramid Roll</td>
<td>12&quot; x 12&quot;</td>
</tr>
<tr>
<td>Buffalo Roll</td>
<td></td>
</tr>
<tr>
<td>Hot And Cold Joggle Press</td>
<td>110 Ton</td>
</tr>
<tr>
<td>Intercontinental Joggle Press</td>
<td></td>
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</tbody>
</table>
Cyril Bath VTL 800-180CJ-360 Stretch Wrap Sheet Press

Die Table: (90 degree indexing for longitudinal forming)
Thrust: 800 Tons
Stroke: 100"
Size: 24” x 180”
Tilt: +/- 15 Degrees
Control: Servo
Max Rate: 12 IPM Full Capacity Forming
30 IPM Positioning

Sheet Jaws: (Main Set)
Type: Direct Acting
Effective Length: 180” segmented
Configuration: Power Curvable (up or down)
Minimum Radius: 55”
Clamp Opening: 2 1/2” max
Horizontal Angulation: + / - 10 Degrees
Maximum Distance Between Jaw Centerlines: 360” w. 14” tension cylinder stroke remaining.
Minimum Distance Between Jaws (Horizontal): 1”
Swing : 90 Degrees
Rotation: +10 Degrees

Auxiliary Sheet Jaws: ( included for tight radius or thin sheet forming)
Type: Direct Acting
Effective Length: 74” segmented
Configuration: Power Curvable (up or down)
Minimum Radius: 22”
Clamp Opening: 5/8” max
Horizontal Angulation: +10 degrees
Maximum Distance Between Jaw Centerlines: 300” w. 14” tension cylinder stroke remaining.
Minimum Distance Between Jaws (Horizontal): 1”
Swing : 90 degrees
Rotation: +10 Degrees

Jaw Carriages -
Pull: 400 Tons
Stroke: 66”
Oscillation: +12 Degrees
Control: Servo
Maximum Rate: +/- 30 IPM

Bulldozer: ( Gantry type for Stretch Draw forming)
Force: 400 Tons
Stroke: 60”

Electrical: One (1) 75 hp, two (2) 125 hp, two(2) 100 hp, one (1) 10 hp motors (not including bulldozer power unit)
Utilities: 460 VAC, 3 ph, 60 Hz, water at 60 gpm/40 psi/85 deg F, air at 80 PSIG
Options Included: CNC controls, tangency sensor/tracker attachment, CO2 fire suppression system, way covers, extensive spare parts inventory, drawings & manuals
Titanium is the fourth most abundant structural metal on Earth, exceeded only by aluminum, iron, and magnesium. Workable mineral deposits are dispersed worldwide and include sites in Australia, the United States, Canada, South Africa, Sierra Leone, Ukraine, Russia, Norway, Malaysia, and several other countries.

Titanium is used as a material of construction because of its:
- Excellent Corrosion Resistance
- Superior Strength-to-Weight Ratios
- Superior Erosion Resistance
- High Heat Transfer Efficiency

When it’s alloyed with 6% aluminum and 4% vanadium, for example, titanium has half the weight of steel and up to four times the strength. Add to that titanium’s biocompatibility—the ability to be ignored by the human body’s immune system—and an extreme resistance to corrosion, and you have what architectural-metals consultant Gary Nemchock calls the “armor for the 21st century.” Titanium is now the metal of choice for hip and knee replacements, and it’s in the 35,000 panels that cloak Frank Gehry’s new Guggenheim Museum in Bilbao, Spain. Denver-based Volant Sports, which already makes titanium-fortified skis, is looking into all-titanium skis that weigh half as much and are twice as strong as its steel skis.

The predominant minerals are rutile, which is about 95 percent titanium dioxide (TiO2), and ilmenite (FeTiO3), which contains 50 to 65 percent TiO2. A third mineral, leucoxene, is an alteration of ilmenite from which a portion of the iron has been naturally leached. It has no specific titanium content. Titanium minerals occur in alluvial and volcanic formations. Deposits usually contain between 3 and 12 percent heavy minerals, consisting of ilmenite, rutile, leucoxene, zircon, and monazite.

Titanium is used in the manufacturing of:
- Jet Engines
- Bicycles
- Piping Systems
- Aircraft Frames
- Golf Clubs
- Lacrosse Sticks
- Roller Blades
- Valves
- Marine Equipment
- Artificial Hips & Knees
- Automotive Components
- Watches
- Heart Valves
- Jewelry
- Wheel Chairs
- Dental Implants
- Eye Glass Frames
- Metal Matrix Composites
- Pace Makers
- Chemical Processing Equipment
- Heat Exchangers
- Pulp and Paper Processing Equipment
- Pharmaceutical and Food Processing Equipment
- Auto Racing
- 777 Main Landing Gear
- The Future
- Boeing Explorer Helicopter

Every 2,000 lb. of empty weight that we take off the 747, we can add another seat and that seat will return about $5 million in revenue for our customers.
The History of Titanium
Titanium ore was first discovered in 1791 in Cornish beach sands by an English clergyman, William Gregor. The actual identification of the oxide was made a few years later by a German chemist, M.H. Klaproth. Klaproth gave the metal constituent of this oxide the name titanium, after the Titans, the giants of Greek mythology. Pure metallic titanium was first produced in either 1906 or 1910 by M.A. Hunter at Rensselaer Polytechnic Institute (Troy, N.Y., U.S.) in cooperation with the General Electric Company. These researchers believed titanium had a melting point of 6,000°C (10,800°F) and was therefore a candidate for incandescent-lamp filaments, but, when Hunter produced a metal with a melting point closer to 1,800°C (3,300°F), the effort was abandoned. Nevertheless, Hunter did indicate that the metal had some ductility, and his method of producing it by reacting titanium tetrachloride (TiCl₄) with sodium under vacuum was later commercialized and is now known as the Hunter process. Metal of significant ductility was produced in 1925 by the Dutch scientists A.E. van Arkel and J.H. de Boer, who dissociated titanium tetraiodide on a hot filament in an evacuated glass bulb. In 1932 William J. Kroll of Luxembourg produced significant quantities of ductile titanium by combining TiCl₄ with calcium. By 1938 Kroll had produced 20 kilograms (50 pounds) of titanium and was convinced that it possessed excellent corrosion and strength properties. At the start of World War II he fled Europe and continued his work in the United States at the Union Carbide Company and later at the U.S. Bureau of Mines. By this time, he had changed the reducing agent from calcium to magnesium metal. Kroll is now recognized as the father of the modern titanium industry, and the Kroll process is the basis for most current titanium production. A U.S. Air Force study conducted in 1946 concluded that titanium-based alloys were engineering materials of potentially great importance, since the emerging need for higher strength-to-weight ratios in jet aircraft structures and engines could not be satisfied efficiently by either steel or aluminum. As a result, the Department of Defense provided production incentives to start the titanium industry in 1950. Similar industrial capacity was founded in Japan, the U.S.S.R., and the United Kingdom. After this impetus was provided by the aerospace industry, the ready availability of the metal gave rise to opportunities for new applications in other markets, such as chemical processing, medicine, power generation, and waste treatment.

The main advantages of titanium are a low density (4500 kg/m³) compared to steel (7800 kg/m³), good corrosion resistance (it is inert to body fluids) and high strength (depending upon alloying). A difficulty when manufacturing titanium components is that it is a reactive metal, particularly at high temperatures, taking up oxygen and nitrogen from the atmosphere and hydrogen if moisture is present. The absorption of small amounts causes a reduction in fatigue strength. Hence where parts are manufactured by casting or welding, the environment must be purged with an inert gas, argon is normally used.

Applications and Processes
Use of titanium started in the automobile industry in the early 1970s with the use of small machined parts for racing cars, such as gear linkages, where the high costs of materials and manufacture were acceptable. Early attempts at fabricating suspension components by welding at Lotus in the early 1980s were unsuccessful as the appropriate precautions were not taken and parts cracked. By the early 1990s Barnard had devised an effective method of providing an inert atmosphere while welding and fabricated suspension uprights. As the suspension upright is “unsprung weight”, weight savings here are particularly worthwhile. More recently developments in casting have broadened the availability of cast titanium parts, but the reactivity of molten titanium means that it has to be melted under vacuum.

A section of the segmented cold crucible and the induction coil

The metal is heated quickly, begins to melt and initially fills the base of the crucible, where a small volume resolidifies and forms a local, thin ‘skull’ of metal. As melting nears completion, the electromagnetic (Laplace) force in the molten metal concentrates it in the centre of the crucible, reducing metal mould contact, figure 2.
For many years the manufacture of precision castings in titanium has relied on the vacuum arc remelting (VAR) process. This slow and costly technique severely limits development of the advanced casting capabilities that modern end users demand. In particular the aerospace industry has been extremely aggressive in its technical design requirements for components both large and small, some in flight critical applications on programmes such as the Eurofighter, the Airbus A340 and A3XX, and the US’s Joint Strike Fighter. To date, success on these programmes has been impressive in terms of increased size capability but there has been a lack of metallurgical integrity and improvements in dimensional tolerances. Consequently, there is a vital need for a step improvement in the moulding, melting and pouring of titanium precision castings, work towards which has typically employed an induction melting process usually referred to as inductive skull remelting (ISR).

The Process
In Europe, the need is being met by a small company called Taramm (Tirane et Alliages Rares MicroMoules) which is providing a viable production capability using a unique combination of cold crucible induction melting and centrifugally assisted pouring. The heart of the process is a special vacuum melting and pouring furnace designed by Taramm. The furnace structure accommodates the melting and pouring equipment and uses conventional vacuum pumping systems. In a conventional one piece copper crucible the magnetic field generated by the field current in the heating coil is cancelled out by the magnetic field associated with the induced current in the crucible. The magnetic flux that would be necessary to heat and melt a conductive metal charge thus does not exist. In contrast the Taramm copper crucible, figure 1, is segmented, each segment being water cooled and insulated from each adjacent segment. Under power, this design causes the induced current to loop around each segment as shown by the arrows A, B, C, and D, and allows the generation of an induced current, creating the required magnetic field in the metallic charge.

Once melting is complete the charge is partially levitated and, due to the minimal heat exchange between the metal and the crucible, the metal becomes superheated. This can be controlled for charge weights up to 5kg. The Taramm technique therefore provides significant advantages in terms of the ‘filling’ of thin sections in the mould, and the overall length of flow of the molten metal, compared with the VAR process, which is incapable of superheating. The constant and vigorous stirring of the titanium by the induced electromagnetic forces also gives the benefit of optimum chemical and thermal homogeneity in the metal. When the requisite molten metal temperature is achieved, the crucible is tilted and the titanium poured into a ceramic mould rotating at high speed. In order to maintain the temperature of the melt the electrical power is applied throughout the pouring operation.

On entering the mould the molten titanium is immediately subjected to centrifugal forces. The filling of the mould cavities is accelerated by the continually increasing pressure exerted on the molten metal and directed towards the outer diameter of the mould. This centrifuge effect, combined with the superheated nature of the titanium, promotes the filling of section cavities as thin as 0.5mm, with attendant fine detail and form. Centrifugation is maintained until the titanium solidifies. Satisfactory centrifugal casting demands a symmetrical mould which is balanced radially within a prescribed annulus. An additional advantage of centrifugation is a more efficient use of metal due to the parabolic free surface of the liquid metal in the mould. The metal charge weight is carefully adjusted for each mould configuration to ensure the filling of each casting cavity and its ‘feeder’, while leaving a significant portion of the central downsprue devoid of metal. This technology has further benefits. While the conventional VAR process demands the use of a custom made electrode, sized to fit the crucible, the Taramm process is able to use forged or rolled premium quality off cut, material which is a fraction of the cost of the VAR electrode. Also, in VAR a ‘stub’ of the electrode is left as a remnant of the electrical circuit after melting and, considered with the ‘skull’ material covering the interior surface of the crucible, a significant proportion of the original electrode is left unused. After the Taramm process the only unused metal is contained in the minimal skull in the base of the crucible amounting to a large material saving. So far the cold crucible induction process has been used mainly to produce Ti6Al4V commercially pure titanium and titanium aluminide eutectic alloys. However, nickel base alloys, such as IN 718, are compatible with the process and there is therefore no need to use different types of melting furnace for these metals. The metal flow and filling performance produced by the combined effect of superheating and centrifugal pouring in the Taramm casting process enables the pre heat temperature of the recipient mould to be significantly reduced, compared with the VAR process. Preheat costs are therefore lower but, most importantly, the formation of alpha case, due to the oxide-forming metal-mould reaction, is significantly reduced. As a result, ‘chemical milling,’ which has now become the mandatory surface cleaning operation for alpha case removal is used much more sparingly. This allows for the retention of much more of the cast surface layer and means cast tolerances and physical dimensions are better maintained. This process is effective for castings from a few grams to 2kg in weight, and wall section thicknesses as low as 0.5mm are routinely achieved. Form and detail are extremely well defined. Due to the pressures applied by the centrifuge and subsequent densification by hot isostatic pressing (HIP), castings show little or no evidence of porosity and micro-shrinkage even on a microscopic scale. The use of premium quality melt stock and the robust nature of the ‘face coat’ the Taramm developed shell moulding system combine to give good metallurgical integrity when assessed for casting defects such as non-metallic inclusion. Electromagnetic stirring eliminates any propensity for segregation, and the casting technique yields consistently uniform grain size and structure. Figure 3 shows a nozzle casting for a missile application. This technology also lends itself to other industries such as the medical and leisure industries.
Titanium Bone Implants

A portion of a human bone was replicated in titanium to demonstrate that the complex surface of an actual bone could be recreated in a structural implant material. Although titanium is currently used for bone replacement, implants are simple geometric approximations of the bone shape. Mismatches between implants and real bone often cause stress concentrations and result in premature implant failure. In this project, an accurate digital model of a bone was sliced into discrete layers. A reproduction of the bone was constructed using Selective Laser Sintering (SLS), a layered manufacturing process developed at The University of Texas at Austin. Rapid prototyping technologies such as SLS are ideal for producing complex parts and prototypes because no specific tooling or patterns are required. Because the titanium piece is an exact duplicate, it will fit the patient’s bone structure exactly and have a longer service life.

The ball section and peg were inverted to create a digital mold. This was a rather complex process because the mold geometry had to meet the specifications of the titanium foundry. The size and shape of the neck, where molten titanium would enter the mold, had to be shaped to prevent pressure build-up and ensure proper metal flow. In addition, a small vent hole was added to allow the titanium to completely fill the mold. Finally, to conserve material, the size of the mold was reduced by 50 percent. The finished 3D digital mold was converted to an STL format so it could be constructed in a Selective Laser Sintering workstation.

Strength, roughness and shrinkage were measured on material samples before and after each processing step. The values obtained were used to refine the process. Shrinkage could be accurately predicted, and roughness and strength were brought to acceptable levels for titanium casting. Below are two sets of femur and ball inserts made in nylon with the Selective Laser Sintering process.

The titanium castings were prepared metallographically. Optical microscopy revealed a thin alpha case on the surface of the casting, typical of as-cast titanium alloys. The thickness of the alpha case was comparable to those obtained using standard mold materials. Roughness measurements indicated an as-cast surface roughness (Ra) of 8 microns. Below are pictures of cast titanium (dark) and broken zirconia molds (white).

It is hoped that a damaged bone can be replaced with a customer-specific titanium implant using the outlined production method. An X-ray, CT or MRI scan of a symmetric, non-damaged bone could be reversed and used to construct the mold for a damaged bone. Essentially any damaged bone (a finger, toe, hand, arm, foot, jaw, or skull) could be replicated in a titanium implant. The high strength to weight ratio and biocompatibility of titanium make it a reliable implant material, and now, using digitally designed zirconia molds, better fitting implants can be produced.

The 3D digital data was transferred to the UT ASE/EM LRC to be digitally processed. The original 3D digital model was too complex to manufacture using the laser-sintering machine available at UT. Thus, the first step was to reduce the number of facets representing the femur bone to 30,000 while maintaining part accuracy. The 3D digital model was then sectioned by digitally separating the ball section from the shaft of the femur. A locator peg was added to the ball section to indicate where it would contact the shaft portion of the femur.
A newer trend increasingly hitting the links is cast titanium clubs. Considered a "space-age" metal, titanium has grown in importance and value over the years, according to the Investment Casting Institute, Dallas. Process improvements in vacuum melting (because titanium is so reactive and oxidizes very quickly, it must be melted under a vacuum) and molding has spurred tremendous growth in the production of aerospace, medical and sports equipment applications. The growth in the production of titanium golf heads has been described by many as "phenomenal." Titanium is gaining attention due to its high-strength, low-density benefits (titanium's strength is on par with steel but at half the weight). It allows golf designers to increase the size of the club while maintaining the weight and strength. "The trend is toward a larger head to give golfers more confidence in striking the middle," said Schupmann. An article from the Journal of The Minerals, Metals & Materials Society described the benefits of a hollowed cast titanium head: "The net result is a club that is claimed to give greater distance (greater clubhead speed because of the longer arc), but also a straighter shot because of the greater resistance to twisting of the shaft, and a higher moment of inertia in the head. In golf terms, the golfer can now drive the ball farther and further without swinging harder because of a bigger sweet spot." "Titanium gives designers a whole new pallet to design with in which they can locate the weight in the head to impart and improve certain playability characteristics," said Petrucci. "They can increase the overall size of the head-larger face, bigger sweet spot-to improve play."
Composite Hulls

2+2 = 10 (What's a Composite)?

Modern composites owe their existence to the aerospace industry, where lightness rules. Because heavy airplanes can't carry much payload, you'll find more aluminum planes than lead ones. Carbon fiber, the ultimate high-tech composite, is sometimes called "black aluminum" because it works like aluminum -- but weighs about 25 percent less.

Compared to older materials, advanced composites, particularly the carbon-fiber used in the Airbus, are stronger, lighter, easier to engineer, and more resistant to fatigue. They do not expand or contract when temperature changes, which is important in airplanes that may sit on a tropical runway one minute, and fly in the subzero stratosphere 10 minutes later. Last -- and this can be crucial -- composites don't corrode.

Composites are combinations of two materials in which one of the materials, called the reinforcing phase, is in the form of fibers, sheets, or particles, and is embedded in the other materials called the matrix phase. The reinforcing material and the matrix material can be metal, ceramic, or polymer. Composites are used because overall properties of the composites are superior to those of the individual components.

The following are some of the reasons why composites are selected for certain applications:

- High strength to weight ratio (low density high tensile strength)
- High creep resistance
- High tensile strength at elevated temperatures
- High toughness

Typically, reinforcing materials are strong with low densities while the matrix is usually a ductile, or tough, material. If the composite is designed and fabricated correctly, it combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material. The downside is that such composites are often more expensive than conventional materials. Examples of some current application of composites include the diesel piston, brake-shoes and pads, tires and the Beechcraft aircraft in which 100% of the structural components are composites.

The strength of the composite depends primarily on the amount, arrangement and type of fiber (or particle) reinforcement in the resin. Typically, the higher the reinforcement content, the greater the strength. In some cases, glass fibers are combined with other fibers, such as carbon or aramid (Kevlar29 and Kevlar49), to create a "hybrid" composite that combines the properties of more than one reinforcing material. In addition, the composite is often formulated with fillers and additives that change processing or performance parameters.

Three types of composites are:

- Particle-reinforced composites
- Fiber-reinforced composites
- Structural composites

Unidirectional Carbon Fibers

Continuous Reinforced Cementitious HighPerf Material
Composite Hulls

Particle Reinforced Composites:

Particles used for reinforcing include ceramics and glasses such as small mineral particles, metal particles such as aluminum, and amorphous materials, including polymers and carbon black. Particles are used to increase the modulus of the matrix, to decrease the permeability of the matrix, to decrease the ductility of the matrix. Particles are also used to produce inexpensive composites. Reinforcers and matrices can be common, inexpensive materials and are easily processed. An example of particle reinforced composites is an automobile tire which has carbon black particles in a matrix of polyisobutylene elastomeric polymer. Another example is spheroidized steel where cementite is transformed into a spherical shape which improves the machinability of the material. Another example for particle-reinforced composite is concrete where the aggregates (sand and gravel) are the particles and cement is the matrix. Particle reinforced composites support higher tensile, compressive and shear stresses.

Fiber-reinforced Composites:

Reinforcing fibers can be made of metals, ceramics, glasses, or polymers that have been turned into graphite and known as carbon fibers. Fibers increase the modulus of the matrix material. The strong covalent bonds along the fiber's length gives them a very high modulus in this direction because to break or extend the fiber the bonds must also be broken or moved. Fibers are difficult to process into composites which makes fiber-reinforced composites relatively expensive. Fiber-reinforced composites are used in some of the most advanced, and therefore most expensive, sports equipment, such as a time-trial racing bicycle frame which consists of carbon fibers in a thermoset polymer matrix. Body parts of race cars and some automobiles are composites made of glass fibers (or fiberglass) in a thermoset matrix.

The arrangement or orientation of the fibers relative to one another, the fiber concentration, and the distribution all have a significant influence on the strength and other properties of fiber-reinforced composites. Applications involving totally multidirectional applied stresses normally use discontinuous fibers, which are randomly oriented in the matrix material. Consideration of orientation and fiber length for a particular composites depends on the level and nature of the applied stress as well as fabrication cost. Production rates for short-fiber composites (both aligned and randomly oriented) are rapid, and intricate shapes can be formed which are not possible with continuous fiber reinforcement.

Structural Composites:

The properties of structural composites depend on:
- Common constituents
- Geometrical design

Common structural composite types are:
Laminar: Is composed of two-dimensional sheets or panels that have a preferred high strength direction such as is found in wood and continuous and aligned fiber-reinforced plastics. The layers are stacked and cemented together such that the orientation of the high-strength direction varies with each successive layer. An example of a relatively complex structure is modern ski, another example is plywood.

Sandwich Panels: Consist of two strong outer sheets which are called face sheets and may be made of aluminum alloys, fiber reinforced plastics, titanium alloys, steel. Face sheets carry most of the loading and stresses. Core may be a honeycomb structure which has less density than the face sheets and resists perpendicular stresses and provides shear rigidity. Sandwich panels can be used in variety of applications which include roofs, floors, walls of buildings and in aircraft, for wings, fuselage and tailplane skins.
Composite Hulls

Matrices (Sandwichelements)

- Foam Matrix
- Honeycombs
- 3D Woven Fabrics
- 3D Glass Fabrics (Reinforcement/Matrixhybrid)
- Extruded by Matrix-Component (Resin)

Manufacturing Advanced Composites:

- Stress Analysis
- Choice of Material
- Production of Molds, Cold- or Heatforming of Matrixmaterial or Prepregs of Reinforcement

Production process of a Racingboat

- Moldproduction
- Vacuumforming of Reinforcement
- Fibercoating
- Application of additional Matrixcoats
- Surfacefinish
- Completion
Composite Hulls

Applications:

Military and Commercial Aircrafts

Spaceships and Missiles

Marine (Speed Boats, Sailboat, Military)

Bikes, Automobiles, Trucks

Architecture, Engineering, Corrosion

High Performance Sports
Inflatable Panels

1. Triangular lattice truss: 219.1 mm (dia), 159.6 mm, 101.6
2. PVC ventilation duct with polythene fixing clips
3. 6mm sheet steel bent to shape
4. Aluminum panel gutter with sealing sheet
5. 10 mm steel plate bracket for gutter
6. Three-later inflated ETFE cushion
7. Aluminum clamping strip
8. 70 mm (dia) steel cylinder as safety rail
9. Cast-steel node
10. 80 mm (dia) tubular diagonal member
11. Extruded-aluminum frame to opening flap
12. Composite sheet-metal and plastic-sheet gutter; thermal insulation, steel section
13. Pneumatically operated cylindrical opening shaft
14. High-pressure air tube for operating flap
15. PVC edge strip fixed to flange
inflatable panels

A triple glazed ETFE (ethyl tetra fluoro ethylene) foil provided the answer. As well as being strong, lightweight, anti static, and highly transparent to UV light it is not degraded by sunlight, has better insulation properties than glass, and is recyclable.

- ETFE weights less than 1% of the equivalent tube area of glass, needs less steel to hold it up and still needs light through
- ETFE is recyclable and long lasting with a life span of over 25 years
- ETFE is tough. A single inflated pillow can take the weight of a rugby team
- ETFE is non-stick and therefore self cleaning

Three layers of ETFE are heat welded together at the edges and inflated into giant pillows 2 metres deep. These foil windows have been put in by 22 professionally qualified balloonists, who spent months cutting over the huge steel web like little spores.

- the transparent foil pillows, 2m deep, act like a blanket, insulating the covered 6 homes
- inflows are triple glazed - the two layers of air they contain give maximum insulation
- the hexagon fixing points have been designed so that new, more advanced 'breathing' materials could replace ETFE in the future
Polyurethanes are formed by reacting a polyol (an alcohol with more than two reactive hydroxyl groups per molecule) with a diisocyanate or a polymeric isocyanate in the presence of suitable catalysts and additives. Because a variety of diisocyanates and a wide range of polyols can be used to produce polyurethane, a broad spectrum of materials can be produced to meet the needs of specific applications. Most polyurethanes are thermoset materials; they cannot be melted and reshaped as thermoplastic materials can be. Polyurethanes exist in a variety of forms including flexible foams, rigid foams, chemical-resistant coatings, specialty adhesives and sealants, and elastomers. Rigid polyurethane foams are used as insulation for buildings, water heaters, refrigerated transport, and commercial and residential refrigeration. These foams are also used for flotation and for energy management. Flexible polyurethane foams are used as cushioning for carpet and in upholstered furniture, mattresses, and automobiles. They are also used for packaging. Polyurethane adhesives and sealants are used in construction, transportation, marine, and other applications where their high strength, moisture resistance and durability are required. The term "polyurethane elastomers" includes such diverse products as thermoplastic polyurethane, cast elastomers and Reaction Injection Molded (RIM) products. These materials go into a wide variety of applications from footwear and skate wheels to machinery housings, to athletic tracks to electronic media.
Eva Hesse
Right After, 1969
Fiberglass and polyester resin with metal hooks

What is fiberglass?
Fibers similar to wool or cotton fibers but made from glass; sometimes called fibrous glass. Glass fiber forms include cloth, yarn, mat, milled fibers, chopped strands, roving, woven roving.

What is polyester?
(Unsaturated) A resin formed by the reaction between dibasic acids and dihydroxy alcohols, one of which must be unsaturated (typically maleic anhydride) to permit cross-linking.

What is resin?
Any of a class of solid semisolid organic products of natural or synthetic origin, generally of high molecular weight having no definite melting point. Used in reinforced products to surround and hold fibers. Most resins are polymers.
Eva Hesse
Untitled, 1970
Latex and filler over rope and string with metal hooks

**Latex** can be used as a water based coating on a variety of fibre types and fabric constructions often utilized by the textile industry. They are applied by knife coating, padding, spraying, paste, foaming, lick coating or rotary screen printing. The coatings are water resistant and durable, imparting good handle and dimensional stability to the fabric in addition to flame retardancy.

There are also prevulcanised natural rubber latex compounds primarily used in the dipping industry. These compounds are available with a wide range of dry film physical properties from low to high modulus. It has excellent clarity, high tensile strength, good resistance to aging and long shelf life. The compounds can be used for either heat sensitised dipping or in the coagulant dipping process. It can also be sprayed, brushed on, coated onto textiles or used for manufacture of sheet. Cold casting is another option with hardness and flexibility of the finished product able to be varied.

**What is filler?**
Relatively inert organic or inorganic materials which are added to plastics resins or gelcoats for special flow characteristics, to extend volume, and lower the cost of the article being produced.
Donald Droll's loft

The Solomon R. Guggenheim Museum, New York
Marcel Wanders
Knotted Chair, 1996
Aramid twisted around carbon rope, knotted, then impregnated in epoxy and hung in a frame to harden
**Aramid** fibers are a type of nylon of which the molecular structure are comprised of linked benzene rings and amide bonds.

The U.S. Federal Trade Commission (FTC) distinguished these fibers from conventional aliphatic polyamide fibers, i.e. nylon fibers, in 1974, collectively referring to aromatic fibers as "Aramids."

In 1977, the ISO similarly included this name in its listing of synthetic fibers.

As is described in this technical guide, aramid fibers differ greatly from conventional fibers (nylon) in both their properties and applications. Aramid fibers are broadly classified as either para-compounds in which the molecular skeleton is generally linear, or meta-compounds with a zigzag skeleton.

**Aramid Fiber Characteristics:**
- No melting point
- Low flammability
- Good fabric integrity at elevated temperatures

Para-aramid fibers, which have a slightly different molecular structure, also provide outstanding strength-to-weight properties, high tenacity and high modulus.

Some major Aramid Fiber uses — Flame-resistant clothing, protective vests and helmets, composites, asbestos replacement, hot air filtration fabrics, tire and mechanical rubber goods reinforcement, ropes and cables, sail cloth, sporting goods.

Aramids are used in protective garments for firemen, police, and the military. Lighter and tougher than steel, a seven-layer aramid undervest weighing only 2-1/2 pounds can stop a .38-caliber bullet fired from a distance of 10 feet. Each year, more ways are found to use these fibers in industrial applications as replacements for steel, fiberglass, asbestos, aluminum, and graphite. Yachts use sails of aramid fibers because of their stability; skis with aramid fiber cores have increased flex life, greater strength, and better performance.

What is **impregnate**?
The saturation of fiberglass with a resin.

**Epoxy** is a mixture of liquid resin and hardener which cures to a high-strength plastic solid.

It has high moisture resistance and bonds with wood fiber, fiberglass, reinforcing fabrics and certain metals.

Resin is the base ingredient of epoxy compounds. It is a clear, pale yellow, low-viscosity liquid.

Hardener, depending on the temperature of the working environment, can affect the cure speed.

Fillers are used to thicken the mixture. It gives certain handling characteristics or cured physical properties. Additives are used instead when specific coating properties are desired.
Roto-formed Plastic

Rotationally molded plastic is a fast and affordable method for producing a nearly infinite range of molded plastics.

THE PROCESS

Through a process of heating plastic and slowly rotating it over a mold, it is possible to generate a virtually stress-free complex shape with an even wall thickness. The tools for rotational molding are considerably less expensive than the tools for injection molding or blow molding because only one tool is needed for an entire piece. These two-sided tools are usually cast aluminum, fabricated sheet aluminum and sometimes mild steel. Since the mold does not need to be constructed to withstand pressure, the mold can be considerably lighter weight than for injection molding. Furthermore, since no core mold is needed, slight design modifications can be made to the mold after it has been fabricated. Because the molds are formed using a CNC process, they can be constructed in as short a period as 1-12 weeks. This quick turnaround time and inexpensive construction costs make custom parts affordable.

After the mold has been tooled, it is possible to begin the molding process. A measured amount of powder resin is poured into the mold, depending on the desired thickness of the piece. Many different types of plastic are used, but the most common is polyethylene. Polyethylene is currently the largest selling plastic in the world and is used in such everyday products as soda and milk bottles, grocery bags and food containers. Additives can be mixed with the plastic to make the part weather resistant, flame retardant, or static free. Several molds (usually up to ten) can be placed in the oven at once, then it is heated and rotated biaxially at a controlled speed to insure an even distribution of the material over the mold. After 1-4 hours in the oven depending on the size of the piece, it is then placed on a pre-cooling arm that is also rotating. Finally, the part is placed in a rotating cooler where water cooling is sometimes used.
Roto-formed Plastic

Since rotational molding enables dual wall construction and undercuts it is often possible to fabricate complex shapes with just one tool.

THE POSSIBILITIES:

SHAPES AND SIZES
Virtually any shape is possible with rotational molding. Ovens can hold parts up to 16”. Because the process enables an even wall thickness (from 1/8” -1/2”+), corners are virtually stress-free. Ribs can be added to the design for extra reinforcement. Multi-wall construction is also possible. Insulating foam can be added after the product has cooled.

CONNECTIONS
With proper planning, products that were once assembled from multiple parts can be made with one part. Since the possibility of part failure is reduced, rotationally molded parts have greater longevity over multi-part pieces. It is also possible to insert metal connector pieces into a part.

COLORS AND IMPRINTS
Any color is possible with glossy or matte finish. It is possible to add ultraviolet protection to the resin to prevent yellowing with outdoor use. It is also possible to imprint logos directly into the mold so that stickers do not need to be applied.

(1) Filling a part with insulating foam. (2) Creating a glossy finish on a bumper. (3) Assembling steel connection parts.
THE PRODUCTS:

As generic as a grain silo and as detailed as a kangaroo.

HELPFUL WEBSITES:

http://www.norstarmolds.com/main.htm -- offers used molds for sale including a number of furniture molds.
http://rotationmag.com/ -- magazine website currently under construction, but keep your eyes peeled!
http://www.rotomolding.org/ -- Association of Rotational Molders
http://www.customrotomold.com -- extremely clear website about their design and manufacturing capabilities
http://www.plasticmolding-ez.com/plasticmolding/ -- a clearing house for plastics manufacturers
http://www.bdbcelona.com/ -- this is the distributor of Ross Lovegrove's roto-molded furniture

As smooth as play equipment and as rough as a septic tank.
CASE STUDY:

A growing number of industrial designers have looked to rotational molding for its advantages of producing a strong, lightweight, cost effective product from a singe process. Included in this list of designers are Mark Newson and Ross Lovegrove. Working with BD Ediciones de Diseno of Barcelona, Lovegrove designed a bench, light, planter and bin. Originally conceived as pieces for homes or hotel lobbies, the pieces are marketed largely as outdoor furniture. The hollow core enables the pieces to be transported easily. Once configured, the parts can be filled with sand or water to insure stability.
Pressure Formed Plastic

Definitions

*Pressure Forming:* This process is similar to vacuum forming except with the addition of pressure (typically 50-150 psi) which pushes the sheet into the shape of the mold. Pressure forming creates greater detail allowing for textured surfaces, undercuts and sharp corners which are not as easily created with vacuum forming. When the material is in place, air is evacuated from the sealed space between the sheet and the mold. At the same time, extremely high air pressure is applied to the outside of the material as it is formed to the mold. When the formed part is removed from the mold, it progresses through a series of fully automated secondary operations. Edges and trim are smoothed to perfection with precise CNC routers; slots and grille work are added as needed; bosses, ribs and special fastening devices are permanently bonded; silk and special fastening devices are permanently bonded; silk screened logos and other accouterments are added.

*Vacuum Forming:* In this process, which began in the 1930s, cut-to-size sheets are heated in ovens which use ceramic or gas heaters and zone controls to maintain an accurate measurement and control of the sheet temperature. The sheet is then placed over a mold and a vacuum is applied pulling the sheet into the shape of the mold.

Finishing fabrication services can include welding, chemical bonding, bending, punching, hot stamping, and screen-printing.

*Thermoforming:* converts a flat thermoplastic sheet into more complex three-dimensional shapes by the use of heat and pressure. The process involves the heating of a thermoplastic material to a particular temperature that softens it. The resulting hot and flexible material is forced against the contours of a mold by mechanical (tolls, plugs, solid mold) or pneumatic (vacuum pressure or compressed air) methods. The mold gives the sheet the needed shape and detail. The formed part is then trimmed to eliminate edges, decorated and/or fabricated into an end use article.

*Twin Sheet Pressure Thermoform:* Two material sheets are simultaneously clamped into one frame. A metered air probe is inserted between the two sheets to prevent them from sticking together during the heating cycle to come. The frame is shuttled into an oven so the material can be heated to the proper forming temperature. Then it's shuttled back out of the oven and positioned between two mold halves which are mounted on a top and bottom plate that come together, sandwiching the two halves close, a
powerful vacuum literally "sucks" each sheet into their respective mold half and high pressure is applied through additional air probes. The high pressure along with a special pinch off design and high heat effectively "welds" the two pieces together into a single hollow molded part.

'West Coast Style' Thermoforming: Several different components from varied processes such as sheet metal, RIM, and Pressure Forming are made into a single product. New shapes not formerly associated with pressure forming have emerged such as tall and narrow ventilation ribs with no draft and deep undercuts to accommodate hardware and sheet metal interface requirements. This evolution has been made possible by the ability to produce more intricate precision molds through 3D solid modeling and computerized machining techniques. In the last 5-7 years there has been more innovation and progress than in the prior 60. (Example shown: The Da Vinci console uses a cast aluminum base and handle and a tubular frame with a sheet metal infrastructure. Pressure Forming was used for all the exterior covers. Once formed and trimmed and painted the pressure formed covers were aligned to the frame using ball studs mounted onto precision 3D machined locating pads to assure that the free from organic shapes of the individual covers locate accurately into the assigned places.)

Materials

-Including, but not limited to: ABS, Acrylic, Butyrate, Coroplast, CPE, Cyrolon, Composites, Lucite, Mirror, PET, Plexiglas, Polycarbonate, Polyethylene, Polypropylene, Polyurethane Films, PVC, Styrene, Vinyl Films

-Most commonly used materials: ABS and Polyethylene

-Heavy gauge material (.064"-.500")

-Sheets size virtually unlimited (6'x16' mentioned as a common large-sized sheet)

Cost

-Vacuum forming usually offers lowest tooling costs

-Pressure forming has startup tooling costs as low as 10% of injection molding

-Part runs between 100-1000 are typically most cost effective
Pressure Formed Plastic

-Savings are dramatically increased if the vendor is involved in the design process from the beginning

**Typical Uses:**

Pickup bed liners, interior and exterior truck parts, agricultural equipment, automotive parts, medical, electronic, and scientific equipment enclosures, computer enclosures, exercise equipment housings, lighting lenses, vending equipment, and manufacturing equipment.

**Overall Benefits of Pressure Forming Plastic:**

-Startup tooling costs as little as 10% compared to injection molding.

-Fast turnaround time, with tooling done in 6-8 weeks, and the first part ready to ship 2 weeks after approval of the tooling.

-Easily modified tooling to accommodate revisions.

-Highly cost efficient production runs of 50 to 50,000 units, depending on size and complexity of component.

-Broad material flexibility from .060" to .500 gauge with unlimited size restrictions.

-Complete aesthetic integrity. Looks as good or better than injection molded items.

-New structural applications, along with high appearance look and feel, have started to make pressure forming the process of choice for low and medium volume products.

**Joe Colombo:**

Slinky, kinky, and plastic are the descriptions that Joe Colombo's version of a utopian space-age future calls to mind. In the 1960s, sci-fi fantasies gave rise to molded curves, tubular furniture, and synthetic fabrics. The Italians and Scandinavians were at the forefront of the design revolution and Joe Colombo was their boldest captain. Colombo's "Roto Living Machine for Living," originally designed for his personal use, was Barbarella's dream house. In the eating area,
a mechanized dining table rotates through the wall and into the kitchen. The all-white bedroom features a lemon-drop sleeping apparatus: a bright yellow plastic canopy extends downward from a stainless steel headboard, and a clear plastic curtain slides around the bed, suggesting delicious space-age voyeurism.
Fibres are pulled from a creel through a resin bath and then on through a heated die. The die completes the impregnation of the fibre, controls the resin content and cures the material into its final shape as it passes through the die. This cured profile is then automatically cut to length. Fabrics may also be introduced into the die to provide fibre direction other than at 0°. Although pultrusion is a continuous process, producing a profile of constant cross-section, a variant known as ‘pulforming’ allows for some variation to be introduced into the cross-section. The process pulls the materials through the die for impregnation, and then clamps them in a mould for curing. This makes the process non-continuous, but accommodating of small changes in cross-section.

Materials Options:
- Resins: Generally epoxy, polyester, vinylester and phenolic.
- Fibres: Any.
- Cores: Not generally used.

Main Advantages:
1) This can be a very fast, and therefore economic, way of impregnating and curing materials.
2) Resin content can be accurately controlled.
3) Fibre content is minimised since the majority is taken from a creel.
4) Structural properties of laminates can be very good since the profiles have very straight fibres and high fibre volume fractions can be obtained.
5) Resin impregnation area can be enclosed thus limiting volatile emissions.

Main Disadvantages:
- Limited to constant or near constant cross-section components
- Heated die costs can be high.

Typical Applications:
- Beams and girders used in roof structures, bridges, ladders, frameworks.

Published courtesy of David Cripps, SP Systems
http://www.spsystems.com

Pultrusion: Process Technology

The process begins when reinforcing fibres are pulled from a series of creels. The fibres proceed through a bath, where they are impregnated with formulated resin. The resin-impregnated fibres are preformed to the shape of the profile to be produced. This composite material is then passed through a heated steel die that has been machined precisely to the final shape of the part to be manufactured. Heat initiates an exothermic reaction thus curing the thermosetting resin matrix. The profile is continuously pulled and exits the mould as a hot, constant cross-sectional member. The profile cools in ambient or forced air, or assisted by water. The product emerges from the pulter mechanism and is cut to the desired length by an automatic, flying cutoff saw.

A schematic representation of pultrusion process is given in following figure:

- a) Material In-Feed: Reinforcements are to be in a package designed for continuous feeding of the material. The continuous fibre creels are usually the first station on a process line. After the roving creels there is a creel meant for rolls of mats, fabric or veil. As materials travel forward toward the impregnation area, it is necessary to control the alignment to prevent twisting, knotting and damage to the reinforcements. This can be prevented by using creel cards or vinyl tubes.

- b) Resin Impregnation Material Forming: The impregnation of reinforcement with liquid resin forms the basis of every pultrusion process. A dip bath is most commonly used. In this process, fibres are passed over and under wet-out bars, which cause the fibre bundles to spread and accept resin. A comb or grid plate is generally provided at the entrance and exit ends of the resin bath to keep the roving in alignment as they pass through the tank.

Forming is usually accomplished after impregnation, preforming fixtures consolidate the reinforcement and move them closer to the final shape provided by the die. A proper sizing of the preforming fixtures avoids excess tension on the relatively weak & wet materials, but also allows sufficient resin removal, avoiding too high hydrostatic force at the die entrance. The commonly used materials for forming guides are Teflon, ultrahigh molecular weight polyethylene, chromium-plated steel and various sheet steel alloys.

- c) Die Heating: Die heating is one of the critical process control parameters as it determines the rate of reaction, the position of reaction within the die, and the magnitude of the peak exotherm. Improperly cured material will exhibit poor physical and mechanical properties, yet may appear identical to adequately cured products. Excess heat inputs may result in products with thermal cracks or crazes, which destroy the electrical, corrosion resistance, and mechanical properties of the composites.

- d) Clamping/Pulling Provision: A physical separation of 3 m (10 ft) or more between the die exit and the pulling device is provided in order to allow the hot, pultruded product to cool in the atmosphere or in a forced water or air cooling stream. Thus allows the product to develop adequate strength to resist the clamping force required to grip the product and pull it through the die. The pulling mechanism varies in design, but three general categories of puling mechanisms that are used to distinguish pultrusion machines are intermittent-pull reciprocating clamp, continuous-pull reciprocating clamp and continuous belt or cleated chain.

- e) Cut-off Station: Every continuous pultrusion line requires a means of cutting product to desired length. Both dry-cut and wet-cut saws are available but regardless of design, a continuous grit carbide or diamond edged blade is used to cut pultruded products. The saw is clamped to the pultrusion product during the actual sawing operation.
Pultrusion is a continuous, automated closed-moulding process that is cost effective for high volume production of constant cross section parts. Due to uniformity of cross-section, resin dispersion, fibre distribution & alignment, excellent composite structural materials can be fabricated by pultrusion. The basic process usually involves pulling of continuous fibres through a bath of resin, blended with a catalyst and then into pre-forming fixtures where the section is partially pre-shaped & excess resin is removed. It is then passed through a heated die, which determines the sectional geometry and finish of the final product. The profiles produced with this process can compete with traditional metal profiles made of steel & aluminium for strength & weight.

The pultrusion process has developed slowly compared to other composite fabrication processes. The initial pultrusion patent in the United States was issued in 1951. In the early 1950s pultrusion machines for the production of simple solid rod stock were in operation at several plants. Most of these machines were the intermittent pull type. In the mid-1950s, continuous pull machines were available. The late 1950s were producing pultruded structural shapes and by 1970, there has been a dramatic increase in market acceptance, technology development, and pultrusion industry sophistication.
pultrusion composites
products - anything with a continuous cross-section
Ceramic materials are inorganic, nonmetallic materials. Most ceramics are compounds between metallic and nonmetallic elements for which the interatomic bonds are either totally ionic or predominantly ionic but having some covalent character. The term ceramic comes from the Greek word keramikos, which means burnt stuff, indicating that desirable properties of these materials are normally achieved through a high-temperature heat treatment process called firing.
Manufacturing

Jose Gonzalez

Facilities and Equipment

Ceramic and Composite Powder Synthesis, Processing, and Characterization

- Blending, mixing, and spray drying
- Furnaces, many with atmosphere control: reducing,
  particle-size and surface-area analysis, differential thermal analysis,
  thermogravimetric analysis, mass spectrometry, viscometry, X-ray diffraction

Green-Forming

- High-shear mixing, ball milling
- Extrusion, tape casting, slip casting, fiber winding, cold pressing, and thick-film fabrication

Firing

- Sintering, hot pressing, hot isostatic pressing

Characterization

- Ultrasonic technique: elastic modulus measurement
- Indentation techniques: hardness, fracture toughness
- Mechanical testing: (room- and high-temperature): compression, tensile, bending, biaxial
- Fiber pushout testing: fiber/matrix interfacial strength
- Optical and scanning electron microscopy with X-ray energy-dispersive analysis
- X-ray diffraction

Porosity

Electrical (DC and AC) at cryogenic temperatures, up to 1,000 A, and in magnetic fields to 7 T.

Nondestructive Characterization of Ceramic Materials

New structural ceramic materials for low-emission, fuel-efficient engines, heat-recovery systems, and other energy applications must be both reliable and cost-effective. New electronic ceramics for applications such as fuel cells and superconductors are also being developed. Nondestructive characterization (NDC) methods provide invaluable information on advanced ceramics -- data required for process development and lifetime prediction. Argonne National Laboratory has an active program to develop NDC techniques and methodology for advanced ceramic materials. Researchers are studying both structural ceramics (e.g., monolithics and whisker-based and continuous-fiber-reinforced composites) and electronic ceramics (e.g., superconductors and solid-oxide fuel cells).

Facilities and Equipment

- Unique high-spatial-resolution, computer-controlled, 3-D X-ray computed tomographic imaging facility, for detecting and mapping density variations
- Laser scattering laboratory, computer-controlled, for studying machined ceramic surfaces and subsurfaces
- Infrared imaging laboratory, computer-controlled, for studying thermal shock damage, delaminations, and other characteristics of continuous-fiber ceramic matrix composites, as well as disbonds in thick thermal barrier coatings
- Nuclear magnetic resonance laboratory, with imaging capability, for studying chemical compositions at fiber/matrix interfaces and spatial distributions of chemical compounds used in processing
- Ultrasonic laboratory, computer-controlled, for detecting delaminations, thickness variations, and fiber density in continuous-fiber composites, as well as voids and inclusions in monolithic ceramics
- Acoustic emissions laboratory, for detecting variations in fiber/matrix interfaces, delamination, and damage in continuous-fiber composites
- Image-processing capability (workstation-based), used to provide enhanced diagnostics from image data
“We concluded in our recently completed development project the best combination of power and energy storage in conjunction with low-cost and ease of fabrication appears to be associated with carbide and nitride ceramics,” said Kramer. Because of the cost and performance advantages associated with ceramic plate ultracapacitors, Lockheed Martin teamed with T/J Technologies through an Air Force funded mentor/protege research program to exploit these components for military applications. “We have successfully demonstrated that T/J Technologies’ nanotechnology can be transitioned from the laboratory to an actual piece of deployed military hardware.” Over the past 18 months, scientists and engineers from both companies have successfully scaled up the fabrication process that produced working prototype ultracapacitors. As a result, the Air Force recently funded a second phase of the program to continue fabrication development.

CERAMIC TURBINE:
Gas turbine engines potentially offer many environmental benefits. They are low polluting, adaptable to a variety of fuels, and highly thermally efficient. Mitsubishi began gas turbine research in 1969. From the mid-70s through mid-80s, Mitsubishi developed a metal gas turbine engine for trucks. Engine and road testing proved the technology’s viability. The gas turbine’s performance was superior to that of a diesel engine in many respects. However, its fuel consumption was higher.

ADVANCE CERAMIC TECHNOLOGY
Advanced Ceramic Technology manufactures precision ceramic parts with CNC machining capability for aerospace, lasers, semiconductors and other industries. Materials include alumina, zirconia, glass, ferrites, silicon carbide, silicon nitride, sapphire, cordierite, mullite, etc.
A full range of ceramic and composite fabrication equipment and capabilities is available for powder preparation and classification, including milling and spray drying, fiber winding, tape casting, extrusion, slip casting, cold pressing, hot pressing, hot isostatic pressing, coating application, and programmed sintering and heat-treating in controlled-atmosphere furnaces. The hot press is used to prepare tough, high-density structural ceramics and composites. Providing a controlled atmosphere, a maximum load of 14,000 lb, and a peak temperature of university and industrial researchers use for joint projects.

Radiant heaters transmit energy as infrared waves. A number of factors must be considered when thinking about radiant heat: energy transfer is only "line of sight"; different materials absorb different wavelengths and amount of infrared energy; different emitters will generate different wavelengths; and operating environment and control are environmental factors to consider.
Casting:
Aremco offers the most expansive range of ceramic-based materials used for the production of high power, high temperature electrical devices as well as high temperature fixtures, molds and tooling. These materials, based on alumina, magnesia, silica, zirconia, and silicon carbide ceramics, offer unique properties with respect to operating temperature, thermal conductivity and dielectric and mechanical strength. Aremco’s hydraulic-setting castable ceramics insulate small electrical components such as gas ignitors, high power resistors and halogen lamps, and to produce large powder metallurgy molds, heat treating fixtures and insulation liners for induction coils. Castable ceramics are supplied in powder form and are mixed with water to develop a strong hydraulic bond. Parts maximum electrical and mechanical properties.

Blankets:
Flexible thermal-insulation blankets made of ceramic fibers can be protected against weather and handling by attaching thin metal face sheets. In applications in which the blankets are exposed to gas flows, the face sheets also afford protection against flow-induced stresses and help reduce aerodynamic drag by providing smoother flow surfaces.

Typically, a metal sheet to be attached to a ceramic blanket has a thickness of 5 mils (0.13 mm) or less and is made of titanium, aluminum, chromium, niobium, or alloys of these elements. The blanket can be made of fibers of silica, aluminoborosilicate, silicon carbide, and/or other ceramic materials. Optionally, in preparation for attachment of the metal sheet, the ceramic fabric on the attachment surface of the blanket can be precoated with a thin layer of nickel to improve its bonding properties.

Small dots of a metal or ceramic brazing material are placed on the attachment surface of the blanket (see figure). Preferably, the dots are between 1/8 and 1/4 in. (about 3 to 6 mm) square and positioned either randomly or in a regular pattern at intervals of about 1 in.
**Boards:**

Thermalite vacuum-formed board is a blend of high purity alumina-silica ceramic fibers, combining both organic and inorganic binders for handling strength and board integrity at high working temperatures. It resists oxidation, reduction, and attack from most corrosives except hydrofluoric acid, phosphoric acid, and heavy concentration of alkalis. Water or oil won't damage it and, upon drying, it regains its excellent physical properties.

**Application**
- Linings for ceramic kilns, vacuum furnaces, aluminizing furnaces, heat treating furnaces, and various other kilns and furnaces
- Back-up insulation for castables, plastics, brick, IFB, and other refractories

**Advantages**
- Low thermal conductivity
- Low heat storage
- Excellent thermal shock resistance
- Excellent noise reduction properties
- Lightweight for easy handling
- Easily cut, drilled, sawed, or machined

**Sizes**
- Contains no asbestos
- Standard thicknesses from 1/4" to 4"
- Standard board sizes:
  - 24" x 36"
  - 24" x 48"

**Tapes:**

Nextel™ Woven Tapes are made from the same high-quality, continuous alumina-boria-silica fibers that have made 3M™ Nextel™ Ceramic Textiles the best solution for high temperature applications. They provide simplicity and dependability at two different

**Typical applications include:**
- Electrical insulation
- Hose protection
- Fire zone cable protection
- Pipe wrap
- Automotive
Thin Films:

Template Assisted Nanostructured Ceramic Thin Films
A new class of materials discovered by scientists at Mobil Corporation ideally illustrates the utility of self-assembly in materials design (Kresge et al. 1992; Beck et al. 1992). Silica precursors when mixed with surfactants result in polymerized silica “casts” or “templates” of commonly observed surfactant-water liquid crystals. Three different mesoporous geometries have been reported (Kresge et al. 1992; Beck et al. 1992; McGehee 1994; McGehee et al. 1994; Monnier et al. 1993), each mirroring an underlying surfactant-water mesophase (Figure 4.1). These mesoporous materials are constructed of walls of amorphous silica, only ten or so angstroms thick, organized about a repetitive arrangement of pores up to a hundred angstroms in diameter. The resulting materials are locally amorphous (on atomic length scales) and crystalline on larger (tens to hundreds of angstrom) length scales.

Pastes:

This research project aims at the development of a new technique for the direct production of ceramic or metal parts based on the use of the procedure “Optoform”. This procedure, functionally comparable to stereo-lithography, uses not liquid resins but photopolymerizable pastes, to produce in a very short time functional parts. It provides a totally new solution for the rapid production of metallic and ceramic parts.
Coatings:

Coating Unicool is a purpose developed heat reflective surface coating based on similar technology as that pioneered by NASA to protect the Space Shuttle during re-entry to the earth's atmosphere.

Unicool is a flexible membrane coating containing many millions of hollow ceramic borosilicate micospheres. The unique composition of Unicool provides equivalent radiant heat insulation to that of up to 6" (150 mm) of conventional fibreglass insulation. The equivalent R-20 rating provides excellent protection against radiant heat, thereby significantly reducing both surfaces and interior temperatures and lowering cooling energy requirements.

Unicool may look like a conventional paint, however it is much more. The designed flexibility of Unicool means it can tolerate a high degree of substrate movement. Unicool, where used in combination with selected Unicoat primers, will also function as a long lasting protective surface coating.

Application of our specialised Unicool heat reflective ceramic coating, can reduce cooling costs by up to 35%. The aboved picture shown it will be able to save substantial maintenance and operating for years to come.

The original version of Unicool was developed in the late 1960's and has been continually upgraded to take advantage of improvements in both coating
Lightweight Concrete

Weighs 35-115 pounds per cubic feet
Normal concrete weighs 145-155 pounds per cubic feet

Compressive strength - 10,000psi

Advantages
- Less steel reinforcement
- Decreases foundation size
- Better fire resistance
- 4 times higher heat insulator
- Excellent resistance to weathering

Disadvantages
- Greater cost
- Greater care in placing
- Greater porosity
- Greater drying shrinkage

Methods of Production
- From natural deposits of pumice scoria, volcanic cinders, tuff and diatomite 85-115 pounds per cubic foot
- By expanding blast furnace slag 75-110 pounds per cubic foot
- By expanding shale, clay, slate, diatomaceous shale, perlite, obsidian and vermiculite through heat application 90-110 pounds per cubic foot
- Natural aggregate 90-100 pounds per cubic foot

Some Applications
- Buildings
- Furniture
- Ship building
**Loop Chair**

Willy Guhl, 1954/1998;  
Eternit (cement/fiber bond, asbestos free)  
handmade, stamped signature.  
Seat Height: 7" +  
Dimensions: 21 1/2"W x 24 1/4"H x 31 1/2"D

Both pieces are handmade in Switzerland of Eternit: a light gray, asbestos free, cement/fiber bond. The chair is actually a rocking chair. It is lightweight and easy to move around, making it a perfect lounge chair. The loop table, with 2 recessed drink holders, fits perfectly into the base of the Loop Chair for storage.

The legendary Eternit Beach chair designed by Willy Guhl in 1954 is a classic of modern furniture design. In the collections of the Philadelphia Museum of Art, the Vitra Design Museum and the Boyd Collection, the 1998 redesign by Willy Guhl himself demonstrates again the designer's credo of "achieving the optimum with minimum effort"  
The Loop Chair is unsurpassed as a self-contained and unsupported fibre/cement bond chair. Whether used indoors or outdoors, this chair is a sculpture and work of art.

The material Eternit, is an asbestos free cement/fibre bond, has a smooth, warm surface and is almost indestructible. It is handmade in Switzerland.

**Loop Table**

Willy Guhl, 1999;  
Eternit (cement/fiber bond, asbestos free)  
Handmade, stamped signature.  
Dimensions: 16 1/2"W x 8 3/4"H/ 7 1/8"H x 28 1/2"D
Loop chair

Loop tables

Loop tables

Loop chair
Other Eternit Products

- Framing for residential building
- Eternit planters
- Framing for residential building
- Used as roofing material
- Eternit mold
- Eternit mold
Lightweight Concrete Buildings

Other Lightweight Concrete Furniture

Designed for Knoll's 60th anniversary, Maya Lin's furniture consist of low, elliptical monolithic tables and seats available in earth tones for indoor and outdoor use.

Peter Sandback's aluminum bases for his lightweight concrete tops.
Lightweight Concrete

Definition and Uses. - Lightweight concrete has been used in this country for more than 50 years. Its strength is roughly proportional to its weight and its resistance to weathering is about the same as that of ordinary concrete. As compared with the usual sand and gravel concrete it has certain advantages and disadvantages. Among the former are the savings in structural steel supports and decreased foundation sizes because of decreased loads, and better fire resistance and insulation against heat and sound. Its disadvantages include greater cost (30 to 50 percent), need for more care in placing, greater porosity, and more drying shrinkage.

The principal use of lightweight concrete in Bureau work is in construction of underbeds for floors and roof slabs, where substantial savings can be effected by decreasing dead load. It is also used in some insulated sections of floors and walls. Lightweight concrete may be obtained through use of lightweight aggregates, as discussed in the following sections, or by special methods of production. These methods include the use of foaming agents, such as aluminum powder, which produces concrete of low unit weight through generation of gas while the concrete is still plastic. Lightweight concrete may weigh from 35 to 115 pounds per cubic foot, depending on the type of lightweight aggregate used or the method of production. In Bureau construction, lightweight concretes have been limited to those whose lightness depends on inorganic aggregates which are light in weight.

Types of Lightweight Aggregate. - Lightweight aggregates are produced by expanding clay, shale, slate, diatomaceous shale, perlite, obsidian, and vermiculite through application of heat; by expanding blast-furnace slag through special cooling processes; from natural deposits of pumice, scoria, volcanic cinders, tuff, and diatomite; and from industrial cinders. Lightweight aggregates are sold under various trade names.

(a) Cinders - Cinders used as aggregates are residues from high-temperature combustion of coal or coke in industrial furnaces. Cinders from other sources are not considered suitable. The Underwriters Laboratories limit the average combustible content of mixed fine and coarse cinders for manufacturing precast blocks to not more than 35 percent by weight of the dry, mixed aggregates. Sulfides in the cinders should be less than 0.45 percent and sulfate should be less than 1 percent. Stockpiling of cinders to permit washing away of undesirable sulphur compounds is recommended. Cinders have been used in concrete construction with satisfactory results for more than 50 years. Cinder concrete weighs about 85 pounds per cubic foot, but when natural sand is used to increase workability in monolithic construction the weight is from 110 to 115 pounds per cubic foot.

(b) Expanded Slag - Expanded slag aggregates are produced by treating blast-furnace slag with water. The molten slag is run into pits containing controlled quantities of water or is broken up by mechanical devices and subjected to sprays or streams of water. The products are fragments that have been vesiculated by steam. The amount of water used has a pronounced influence on the products, which may vary over wide ranges in strength and weight. Concrete in which the aggregate is expanded slag only has unit weights ranging from 75 to 110 pounds per cubic foot.

(c) Expanded Shale and Clay - All expanded shale and clay aggregates are made by heating prepared materials to the fusion point where they become soft and expand because of
entrapped expanding gases. With the exception of one product made from shale, the raw material is processed to the desired size before it is heated. In some cases the particles are coated with a material of higher fusion point to prevent agglomeration during heating. In general, concrete made with expanded shale or clay aggregates ranges in weight from 90 - 110 pounds per cubic foot.

(d) Natural Aggregate - Pumice, scoria, volcanic cinders, tuff, and diatomite are rocks that are light and strong enough to be used as lightweight aggregate without processing other than crushing and screening to size. Of these, diatomite is the only one which is not of volcanic origin.

Pumice is the most widely used of the natural lightweight aggregates. It is a porous, froth-like volcanic glass which is usually white-gray to yellow in color, but may be red, brown, or even black. It is found in large beds in the Western United States and is produced as a lightweight aggregate in several States, among which are California, Oregon, and New Mexico. Concrete made with sound pumice aggregate weighs from 90 to 100 pounds per cubic foot. Structurally weak pumice having high absorption characteristics may be improved in quality by calcining at temperatures near the point of fusion.

Scoria is a vesicular glassy volcanic rock. Deposits are found in New Mexico, Idaho, and other Western States. Scoria resembles industrial cinders and is usually red to black in color. Very satisfactory lightweight concrete, weighing from 90 to 110 pounds per cubic foot, can be made from scoria.

When obsidian is heated to the temperature of fusion, gases are released which expand the material. The interiors of the expanded particles are vesicular and the surfaces are smooth and quite impervious. Expanded obsidian has been produced experimentally. The raw material was crushed and screened to size and coated with a fine material of higher melting point to prevent agglomeration.

The rock from which perlite lightweight aggregate is manufactured has a structure resembling tiny pearls compacted and bound together. When perlite is heated quickly it expands with disruptive force and breaks into small expanded particles. Usually, expanded perlite is produced only in the sand sizes. Concrete made with expanded perlite has a unit weight ranging from 50 to 80 pounds per cubic foot. It is a very good insulating material.

Vermiculite is an alteration product of biotite and other micas. It is found in California, Colorado, Montana, and North and South Carolina. The color is yellowish to brown. On calcination, vermiculite expands at right angles to the cleavage and becomes a fluffy mass, the volume of which is as much as 30 times that of the material before heating. It is a very good insulating material and is used extensively for that purpose. Concrete made with expanded vermiculite aggregate weighs from 35 to 75 pounds per cubic foot; the strengths range from 50 to 600 pounds per square inch.

Properties of Lightweight Aggregates - Properties of various lightweight aggregates, as reflected by those of the resulting concrete, vary greatly. For example, the strength of concrete made with expanded shale and clay is relatively high and compares favorably with that of ordinary concrete. Pumice, scoria, and some expanded slags produce a concrete of intermediate strength; perlite, vermiculite, and diatomite produce a concrete of very low strength.
The insulation properties of the low-strength concretes, however, are better than those of the heavier, stronger concretes. The insulation value of the heaviest material (crushed shale and clay concrete) is about four times that of ordinary concrete.

All the lightweight aggregates, with the exception of expanded shales and clays and scoria, produce concretes subject to high shrinkage. Most of the lightweight concretes have better nailing and sawing properties than do the heavier and stronger conventional concretes. (For information on "nailing concrete, see part B of this chapter.) However, nails, although easily driven, fail to hold in some of these lighter concretes.

Construction Control of Lightweight Concrete. - Commercially available lightweight aggregate is usually supplied in three principal sizes depending upon its application. These are fine, medium, and coarse and range in size to ¾-inch maximum. Production of uniform concrete with lightweight aggregate involves all the procedures and precautions that have been discussed elsewhere in this manual in connection with ordinary concrete. However, the problem is more difficult where lightweight aggregates are used because of greater variations in absorption, specific gravity, moisture content, and amount and grading of undersize. If unit weight and slump tests are made frequently and the cement and water content of the mix are adjusted as necessary to compensate for variations in the aggregate properties and condition, reasonably uniform results can be obtained.

Concretes made with many of the lightweight aggregates are difficult to place and finish because of the porosity and angularity of the aggregates. In some of these mixes the cement mortar may separate from the aggregate and the aggregate float toward the surface. When this occurs, the condition can generally be improved by adjusting the grading of the aggregates. This can be done by crushing the larger particles, adding natural sand, or adding filler materials. The placeability can also be improved by adding an air-entraining agent. The amount of fines to be used is governed by the richness of the mix; as the sand content is increased, the optimum amount of fines is reached when the concrete no longer appears harsh at the selected air content. From 4 to 6 percent air is best for adequate workability, and the slump should not exceed 6 inches.

To insure material of uniform moisture content at the mixer, lightweight aggregate should be wetted 24 hours before use. This wetting will also reduce segregation during stockpiling and transportation. Dry lightweight aggregate should not be fed into the mixer; although this will produce a concrete which can be readily placed immediately after being discharged, continuing absorption by the aggregate will cause the concrete to segregate and stiffen before placement is completed.

It is generally necessary to mix lightweight concrete for longer periods than conventional concrete to assure proper mixing. Workability of lightweight concrete with the same slump as conventional concrete may vary more widely because of differences in type, porosity, specific gravity, etc., of the materials. For the same reason, the amount of air-entraining agent required to produce a certain amount of air may also vary widely. Continuous water curing, by covering with damp sand or use of a soil-soaker hose, is particularly advantageous where concrete is made with lightweight ag