FEDERAL MATERIALS R&D: A METAL MATRIX COMPOSITES OVERVIEW

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Abstract

Declining defense budgets and increasing global economic competition have focused increased attention on the efficiency of the U.S. materials manufacturing enterprise and the strength of the associated defense industrial base. The advanced materials industry in the U.S. has developed, by and large, as a result of significant Federal funding focused on basic science and, perhaps most importantly, on specific agency missions. The recent recognition that support of both military and civilian goals - "dual-use" - is good is particularly relevant to the advanced composites industry, and even more particularly to the metal matrix composites industry which has depended to a quite substantial degree on Federal support. Recent and changing trends in Federal and DoD support of advanced composites R&D are reported. Metal matrix materials options in terms of individual constituents and potential applications are identified. Processes by which the materials can be manufactured and associated processing and R&D issues are described. Other technical as well as economic and regulatory barriers that prevent commercialization of metal matrix composites are identified and potential solutions are proffered.

Science & Technology Policy - the Big Picture

The collapse of the Soviet Union and the end of the Cold War have had a dramatic impact on the face of science and technology in the United States. Declining defense budgets and expanding global economic competition have focused increased attention on the efficiency of the U.S. manufacturing enterprise and the strength of the defense industrial base. It is clear that the government has been under increasing pressure over the past few years to help the private sector compete in those global markets. Congress has also become increasingly willing to fund broad-based industrial development projects with dual-use applicability. The difference between past and present is an explicit recognition that this idea of supporting both civilian and military goals is good. This new approach is particularly relevant to the advanced materials industry which has developed as a result of significant Federal funding focused on basic science and specific agency missions.

Echoing statements of a number of past reports [e.g., 1], the Clinton administration has responded to this explicit recognition by providing a blueprint for focusing science and technology (S&T) on three goals [2, 3]: "long-term economic growth that creates jobs and protects the environment, a government that is more productive and more responsive to the needs of its citizens, and world leadership in basic science, mathematics, and engineering." According to Clinton [3], the traditional federal role in technology development - basic science and mission-oriented research by DoD, NASA, and other agencies with eventual "trickle-down" to industry - is no longer appropriate. Key themes of his proposed plan include industrial competitiveness, critical/dual-use technologies, coordinated management of government resources, and partnerships involving private industry, federal and state government, laboratories, and universities; others include tax, fiscal, and government regulatory reform. The current administration has encouraged efforts in technology transfer via such vehicles as Cooperative Research and Development Agreements (CRADAs) [e.g., 4] and Manufacturing Technology Extension Centers (DoC/NIST). Dual use technologies are also promoted through NIST's Advanced Technology Program [5] and ARPA's Technology Reinvestment Program [6]. Other efforts such as NASA's Aerospace Technology Program [7] and DoE's Partnership for a New Generation of Vehicles [8], have been initiated in response to Clinton's policy objectives. Materials figure predominantly in some of these programs. This technology policy approach will be carried through the FY95 and FY96 budgets.

To help carry out this dramatic shift in technology policy, Bill Clinton established the National Science and Technology Council (NSTC), appointing himself as the Chair [9]. The primary objectives of this group are to establish "clear national goals for federal science and technology investments," to coordinate the policy-making process at the highest interagency levels; and to ensure implementation of the established goals. Not surprisingly, for the NSTC to be successful and to ensure that its goals are representative of real domestic needs, input from outside government is necessary. To that end, Clinton established a President's Committee of Advisors on Science and Technology (PCAST), co-chaired by a representative from the private sector and the President's Assistant for Science & Technology [10].

Federal Materials Research and Development and Policy

Advanced materials and/or composites have clearly received significant support from federal R&D programs over many years. In addition, they have been identified on both the DoD [11, 12] and DoC [13, 14] critical technology lists as being important to U.S. competitiveness.[1] The current administration appears to support those claims. If that is so, where do materials fit into the policy framework?

In the Clinton administration materials policy decisions will primarily be made in the Committee on Civilian Industrial Technology (CCIT), chaired by Mary Good (DoC). Several sub-committees of the CCIT are oriented toward applications: Automotive Technology, Construction and Buildings, Electronics, and Environmental Industries and Industrial Bioprocessing. The CCIT's Manufacturing Infrastructure and the Materials Technologies sub-committees are particularly relevant to advanced materials. The purpose of the CCIT is, with input from industry, to support the Clinton technology policy themes outlined above, specifically focusing on interagency coordination, industry needs important to the U.S. economy, barriers to competitiveness, and the manufacturing infrastructure [15].

The Materials Technology (MatTec) sub-committee provides a central focus for materials technology and related issues in the NSTC [16].[2] Like the CCIT, the group will coordinate programs across the Federal government (ala the Advanced Materials and Processing Program [17-19]) and work closely with the private sector to determine needs and barriers. Technology transfer from the government to the private sector has been specifically identified as another of MatTec's goals. Working groups are being organized to address six application areas: aeronautics, automobiles, construction, infrastructure, electronics, and environment.

The role of both the civil and military aeronautics industry in the U.S. economy is clear [20]: it is the largest positive contributor to U.S. balance of trade and is an important source of high quality, high paying jobs requiring highly skilled labor. The Aeronautics Materials and Manufacturing Technologies Working Group (AMMT) is jointly supported by MatTec and the Manufacturing Infrastructure sub-committees. As is the case for the other committees the

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[1] Interestingly enough, DoC ranked advanced materials with respect to their impact on U.S. industry: polymer composites were rated as high impact ("A"), ceramics as moderate impact ("B"), and metals (rapid solidification and MMCs) as low impact ("C").

[2] Note that Federal materials R&D community has been coordinated since the 1950's through other forums.

AMMT will be coordinating Federal investments in aeronautics materials and manufacturing technologies and providing plans to address established national goals. Policies and programs to address commercialization of defense technology (technology transfer) are mentioned as a specific objective. Input from industry, required to establish the national goals, is provided via the task groups: four major industry/government task groups have been formed and include (1) subsonic airframe, (2) supersonic airframe, (3) propulsion system, and (4) industrial base technologies. The scope of their activities were expected to include materials and processes, design and analysis, fabrication and assembly, inspection and test, and integrated design and manufacturing. Five cross-cut efforts that appear to have developed over recent months are directed specifically toward education, the environment, integrated process and product development (IPPD), standardization, and "smart" materials.[3] The AMMT will be providing a draft strategic plan fulfilling their objectives - national goals; coordinated plans, programs, and budgets; technology roadmaps; performance metrics; and definition of the roles of government, industry, and universities - to the CCIT in early September 1994 [20]. The AMMT has already identified, at least on paper, a number of existing programs that are relevant to its goals: the Advanced Technology Program, manufacturing extension partnerships, automated manufacturing facility, and Intelligent Processing of Materials programs from DoC/NIST; the Technology Reinvestment Program, Manufacturing Technology, IHPTET, advanced metallic and composite structures programs from DoD and ARPA; technology commercialization activities and the continuous fiber-reinforced ceramic composites program from DoE; aging aircraft programs from DoT/FAA; high speed research, advanced subsonic aircraft technologies, Advanced Composites Technology, HITEMP, aging aircraft, and general research and technology base programs from NASA; and focused university research from NSF.

Federal Materials Research & Development Programs

The first Federal materials R&D programs were initiated in the early 1900s. Since then materials R&D has been strongly supported to address specific missions of various agencies. The scope of those efforts has been all-inclusive, covering every aspect from extraction through recycling. As should be obvious by now, there has been an increased recognition that stronger interagency coordination of materials R&D is required, especially with respect to declining budgets and elimination of duplicative efforts, as well as to improving industrial competitiveness. This changing environment led to the formulation of the Advanced Materials and Processing Program, put together several years ago through the Committee on Materials (COMAT) [17, 18]. Identified research components for this program included, in order of importance, synthesis and processing; theory, modeling, and simulation; materials characterization; and education and human resources.[4] The AMPP outlined funding support over FY91-FY93 for materials by agency (Table 1), by research component, and by material class [17-19]. It is interesting to note that DoD, DoE, and NASA have among the largest materials budgets - combined ~68% of the total on average - due in part to a clearly mission-driven focus on specific applications. The NSF budget, directed toward basic research at universities, is also quite large. The AMPP plan was never fully implemented and has since been dropped by the Clinton administration. Materials are still critical to Clinton's technology efforts, though.

The DoD depends, to a significant degree, on the availability of advanced, often highly specialized materials to meet specific military system performance requirements. As a result it has supported the bulk of advanced materials R&D over time. It is, therefore, important to

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[3] Private communication with Mr. Charles Bersch, Institute for Defense Analyses, August 1994.

[4] National user facilities were also included in the list. A significant percentage of the DoE budget in materials is for support of these facilities.

examine their efforts in more detail. As is obvious by now, over the past few years the security environment has been changing. Overall R&D efforts are now focusing on defense problems associated with regional conflicts (e.g., lightweight vehicles with potential for commercial transportation [e.g., 21-23]) and survivability (e.g., lightweight body armor with potential for civilian police protection) [24]. Not surprisingly, key themes are government/industry/university partnerships [e.g., 25-27] and dual-use applications in the interest of maintaining the industrial base as well as improving industrial competitiveness. The focus is no longer on incremental improvements in structural materials and materials R&D directed at heavy armaments for global warfare though preservation of aging assets for those functions has become increasingly important. Emphases on transitioning developed materials to real systems (i.e., upgrades or demonstrations) and affordability (for low volume production) remain unchanged as do emphases on aerospace propulsion via Integrated High Performance Turbine Engine Technology (IHPTET) projects, low observable materials, and composites. The combined materials and structures (M&S) S&T funding profile for DoD[5] since 1980 is shown in Figure 1 [24]. Cumulative composites funding by category - organic (OMC), metal (MMC), ceramic (CMC), and carbon-carbon (C-C) composites- is shown in Figure 2; it has remained roughly constant at about 30% of the total M&S funds. Military funding of 6.2 and 6.3a M&S S&T appears to be stabilizing at about $180 million per year though it has been augmented since FY91 by Congressional add-ons at an apparently decreasing level.

Table 1. R&D Funding (Millions) by Agency [17-19]

Component	FY91	FY92	FY93	FY94**
DoC	44.5	42.6	48.4	56.7
DoD	505.9	530.9	557.7	421.7
DoE*	593.9	862.5	914.0	941.5
DoI	25.0	25.2	24.9	21.5
DoT	10.0	11.0	14.9	12.7
EPA	3.2	3.5	4.5	4.5
HHS	66.6	79.6	85.9	92.9
NASA	116.3	76.3	102.8	131.1
NSF	246.6	265.6	303.6	328.0
USDA	51.4	36.3	37.4	45.8
TOTAL	1663.4	1933.5	2094.1	2056.4

* Includes user facilities
** President's Budget

[5] Funding at the 6.1, 6.2, and 6.3a levels is included for the Army, Air Force, Navy, ARPA, BMDO, University Research Initiatives, SBIRs, and the Defense Logistics Agency.

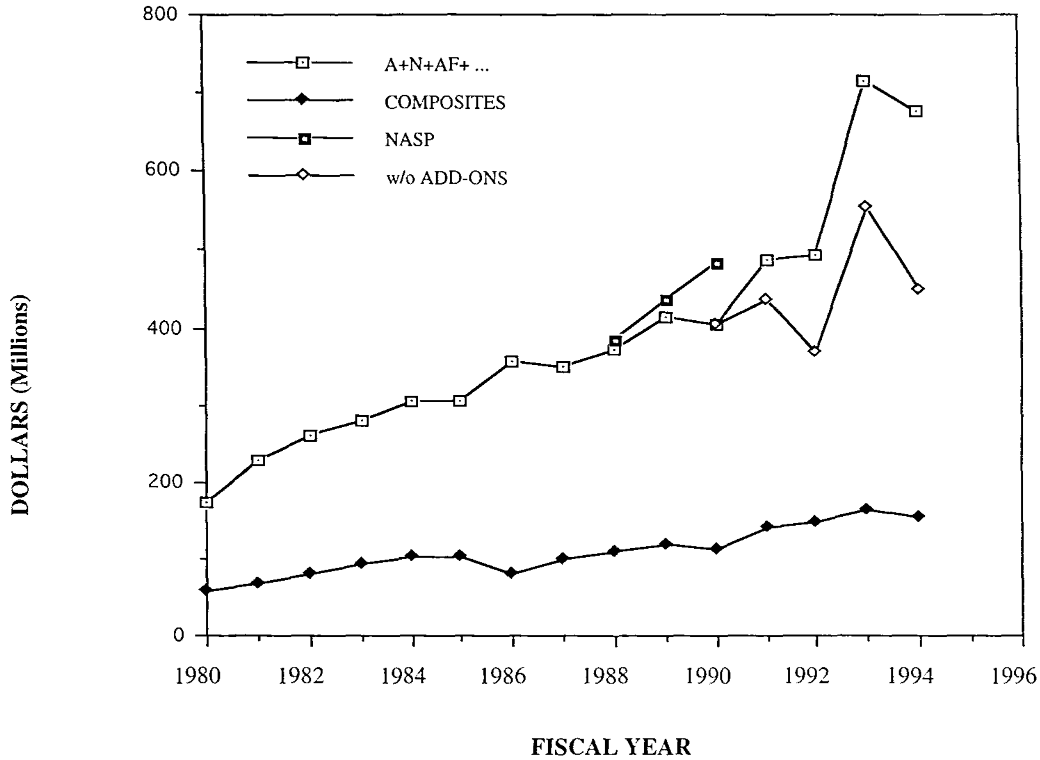

Figure 1. DoD Materials and Structures Funding

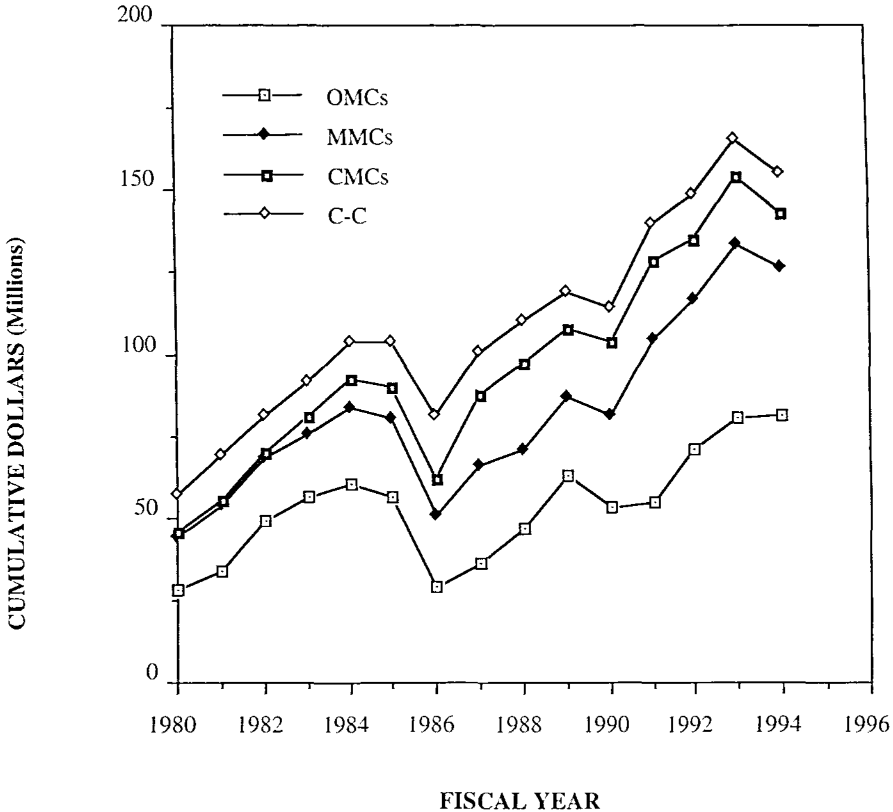

Figure 2. DoD Composites Funding

There is significant coordination of 30 S&T areas within DoD under Project Reliance[6] with the assistance of the Joint Directors of Laboratories (JDL). The advanced materials portion is coordinated through the Technical Panel for Advanced Materials (TPAM), one of 14 panels under JDL [28]. TPAM defines *advanced materials technology* to be "technology which delivers materials exhibiting previously unachieved or undemonstrated . . . properties and performance, producibility, low cost and environmental compatibility, the attainment of which enables the timely development of next generation and future systems" [28]. There are 11 sub-panels for TPAM: NDE/NDI, advanced processing, demonstrations, structural materials, high temperature materials, armor/anti-armor, electromagnetic protection materials, electronic/magnetic/optical materials, special function materials, biomolecular materials and processes, and signature control materials. Each sub-panel has several sub-sub panels under it. composites are specifically identified under Structural and High Temperature Materials Sub-Panels - metal and organic matrix composites and ceramic and carbon-carbon composites, respectively - though they are relevant to others. In terms of the FY94 budget [28], efforts in the two afore-mentioned sub-panel areas represent 33.4% of the total Reliance support for advanced materials.

Perceived technical barriers and target goals in the area of composites cover a broad range [29]. For instance, in the Structural Materials Sub-Panel, the identified barriers include (1) limited modulus and strength, (2) heat dissipation, (3) processing costs, (4) properties at temperature (OMCs), (5) field-level joining and large area repair techniques, (6) limited cost-effective materials and processes (OMCs), and (7) availability of damage-tolerant materials (OMCs) and an adequate database. Targets for 2005 - results of addressing those problems - are as follows: (1) stiff, dimensionally stable, non-ferrous MMCs; (2) high thermal conductivity fibers for MMCs; (3) 50% processing cost reductions; (4) higher temperature-capability OMCs (to 480°C); (5) better, faster field-level repair methods; (6) 30% materials and processing cost reductions over thermosets; and (7) 30% life-cycle cost reductions over thermosets. The Metals/Intermetallics and Ceramics Sub-Sub-Panels of the High Temperature Materials Sub-Panel are limited to materials for applications in which the temperatures are >540°C and >985°C, respectively. Titanium matrix composites (TMCs), ceramic matrix composites (CMCs), and carbon-carbon (C-C) fall under the purview of these groups. Availability of fibers capable of handling high temperatures is a significant issue in all three categories. And there are a number of more fundamental issues related to materials development that must be addressed in order to transition these advanced materials into application. These include, among others, achieving improved as well as reliable and consistent properties and quality, low cost materials and processing methods, and demonstrated joining approaches. Table 2 lists MMC programs that have been funded by DoD over the past few years. There has been one Title III program on the discontinuous-reinforced MMCs (dMMCs) (not listed), involving Advanced Composite Materials Corporation (ACMC), DWA Composite Specialties, Alcoa, and Allied Signal: ACMC and DWA were selected to scale-up their production to 273 kg billets; scale-up was to be completed in 1993 [30].

Metal Matrix Composites, Applications, and Processing

What do we mean by MMCs and why is there so much interest? MMCs, obviously, consist of a metal reinforced by continuous fibers, chopped fibers, or discrete particles or whiskers, or combinations of the above. The reinforcement helps prevent crack propagation and can impart significant stiffness to the composite. The reinforcements may or may not be coated

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[6] Key goals of Reliance are to enhance S&T via ensuring a critical mass of resources to develop "world-class" products; to reduce redundant capabilities and eliminate duplicated efforts; to collocate and consolidate in-house research when possible; and to link S&T programs with end users.

Table 2. Selected DoD Programs on MMCs (6.1, 6.2, 6.3, 7.8)

ARPA	MMC Model Factory (6.2-AMCs, TMCs) Pressureless Infiltration (6.2-AMCs + others) Turbine Engine Initiative (6.2-TMCs)

Air Force	Basic Research (6.1-TMCs)
	  MMC development
	  Interface properties
	  Deformation
	Mechanical Behavior and (6.2-TMCs)
	Damage Tolerance
	  Analytical & FE models
	  Tensile, creep behavior
	  Thermal fatigue w/ and
	    w/o environmental effects
	  Low cycle fatigue
	  High frequency fatigue
	  Fatigue crack growth
	  Notch effects/failure modes
	  Microstructure/processing/
	  properties
	Aircraft Structures (?-AMCs, TMCs)
	  Structural Life Prediction
	  Various Demonstrations
	  e.g., Vertical stabilizer
	       Landing gear

Army	Basic Research (6.1-MgMCs)
	  Microstructure and (6.1-AMCs)
	   mechanical properties
	  Synthesis
	  Defect distribution and material
	  parameters vs mechanical
	  properties
	  Coatings for corrosion protection
	Squeeze Casting (6.2-AMCs)
	Standardization (6.2-AMCs)
	MMC Turbine Shaft (6.2-TMCs)

Navy	Basic Research
	  Interface reactions (6.1-IMCs)
	  Liquid metal (6.1-?)
	   infiltration
	  Microstructural (6-1-AMCs)
	   damping mechanisms
	  Nanocomposites (6.1-Mo MCs)
	  Deformation (6.1-CuMCs)
	   processing
	Technology Base (6.2-AMCs, MgMCs)
	Space Structures (6.2-AMCs, MgMCs)
	  Truss tubes
	Thermal Management (6.2-AMCs)
	  Hardware demonstration
	  Electronic packaging
	   thermal plane
	  Processing
	Aircraft
	  Materials (6.3, 7.8-AMCs, IMCs)
	  Oxidation-resistant, high
	  temperature composites
	  Hybrids
	  Macrolaminates (6.3, 7.8-AMCs)
	  Microlaminates (6.3, 7.8-IMCs)

SDIO/IST (now BMDO)	Materials Development
	Solid state reaction (6.1-Beryllides)
	 bonding
	Microstructurally (6.1-AMCs, IMCs)
	  toughened composites
	    Heat pipe
	Electroplating (6.1-AMCs, IMCs)

SDIO/ TNK	Spacecraft Struct. (6.3-AMCs, MgMCs)
	  Trusses
	  Joints and end fittings
	  Radiator
	Interceptor/Seeker (6.3-AMCs, MgMCs)
	 Structures
	D-2 Projectile (6.3-AMCs)
	Processing (6.3-AMCs)
	  Fabrication processes
	  Thin plies
	  Joining methods

IHPTET/ AF	Materials Development/Characterization
	(6.2, 6.3, 7.8 TMCs)
	Various Component Demonstrations
	  e.g., Compressor rotors
	      Exoskeletal structures
	      Lightweight engine structures
	      Hollow fan blades

IHPTET/ Navy	Joining (TMCs)

NASP	Materials Charact. (TMCs)
	Subcomponent Tests
	Large Demonstration Articles
	Manufacturing Scale-up
	M&S Augmentation (TMCs, CuMCs,
	 Program Be-Al)
	  Materials development
	  Laminate fabrication processes
	  Testing
	  Structural fabrication

NASP/ AF	Institute for the Mechanics and
	Life Prediction of High
	Temperature Composites (TMCs)
	  Materials characterization
	  Mechanical behavior and
	   damage tolerance
	  Multi-parameter testing for
	   structural life verification

to protect them from damage, to control wetting and bonding to the matrix, to act as a diffusion barrier, to prevent reinforcement-to-reinforcement contact, and to transfer stresses from the matrix to the reinforcements. The matrix controls reinforcement spacing and provides protection from the surrounding environment and, in the case of continuous fiber-reinforced composites, transfers and distributes load to the reinforcements. Composite properties can be tailored for specific applications by changing the volume fraction and orientation of the reinforcement, changing the interphase coating, etc. Reinforcement options include Al_2O_3/SiO_2, B, graphite, SiC, TiC, Mo, Nb, Si_3N_4, TiB_2, and W, among others [31]. Matrix material options include aluminum, titanium, copper, magnesium, superalloys, and nickel or titanium aluminides, among others [e.g., 31]. Common combinations include Al_2O_3/SiO_2 (particles or fibers) in Al; graphite (fiber or chopped fiber) in Al, Cu or Mg; SiC (particles, whiskers, or fibers) in Al or Ti; and SiC (fibers) in titanium aluminides. Though discontinuous- (dMMCs) and continuous-reinforced MMCs (cMMCs) composites offer improved and tailorable properties relative to the monolithic metals, the improvement is less for dMMCs; the higher temperature capabilities of the cMMCs are often cited. On the other hand, less costly manufacturing processes can often be utilized for dMMCs: near-net shape (NNS) processes are common. Design and fabrication characteristics can be similar to those of the matrix; in fact, at lower reinforcement volume fractions conventional methods can often be used to produce wrought products. The cMMCs, however, are more difficult to process: accurate fiber placement is critical. Volume fractions of reinforcement are usually larger, ranging from 0.35 to 0.50 for structural composites compared to <0.25 for dMMCs.

Applications

As can be discerned from Table 2, the DoD's interest has been primarily the "high performance" MMCs, specifically, continuous fiber-reinforced composites, mostly for high temperature applications. Perceived benefits for using MMCs extend to various aircraft, missiles, and space structures, ground vehicles, and propulsion systems and include reduced weight, size, fuel, and life-cycle costs; increased range, payload, velocity, and stand-off distance; and improved survivability and maintainability [32]. Table 3 lists some applications and identifies particular benefits for each [31].[7] It is clear from the literature that transportation is a key area for potential application of MMCs [34-49]. Thermal management for electronics [34, 50], farm machinery, medical equipment and other sporting goods/recreational products [34] are other possibilities.

There are features about each of the primary transportation applications that will drive selection of MMCs. A key objective of the transportation industry is maximum payload with a minimum weight structure at the lowest cost under the highest safety considerations. General drivers for using new materials in the transportation industry include the following [35, 51]. (1) new materials must be cost-effective and easily manufacturable at acceptable rates; (2) new materials must be able to provide improved product performance (through improved properties or structural efficiency), quality, or reliability, or they must allow for creative product designs that offer new market opportunities; (3) fuel economy and emissions standards along with waste disposal and recycling requirements will also drive material selection; and (4) the need to bring products more quickly to the market - from 5 to 3.5 years for automobile companies and to less

[7] Ashby [33] has developed conceptual tools which allow one to examine particular reinforcement/matrix material combinations with respect to design and achievable performance. The concept involves three primary parts: performance indices to describe combinations of material properties that maximize performance; materials-selection charts onto which actual material properties and performance indices can be plotted; and upper and lower bounds to define a properties envelope for a particular composite system.

Table 3. Potential Applications and Benefits for MMCs [31]

Potential and Existing Applications \ Benefits	Weight Reduction	Wear Resistance	Stiffness	Tailorable Thermal Conductivity	Elevated Temperature Capabilities	Tailorable CTE	Corrosion Resistance	Resistance to Radiation	High Strength
Aircraft Skins	•				•				•
Bearings	•	•					•		•
Bicycle Frames	•		•						•
Boat Masts & Spars	•		•						•
Brake Rotors	•	•							
Electronics Packaging	•			•	•	•		•	
Electronics/Avionics Racks	•			•	•	•			
Engine Cylinder Liners	•	•							
Fastening Equipment in Chemical Environment-Bolts and Screws	•						•		•
Ground Vehicles	•								•
Landing Gear Struts	•		•						•
Medical Implants	•						•		•
Optical/Guidance Systems Structures	•		•	•		•			
Pistons	•	•							
Satellite Antenna Masts	•		•						
Sea Vehicles	•		•				•		
Space Structures	•		•	•				•	
Transmission Components	•	•					•		
Tubing in Nuclear Plants	•						•	•	
Turbine Engine Components	•	•			•				•
Worm Gears	•	•							•

than the 10-15 years typical for aircraft companies - will also drive materials selection. Bridenbaugh [36] suggests that materials suppliers to the transportation industry must address customer needs; develop a combined materials, process and product design approach; provide subsystems and components (functionality) rather than commodity materials; and produce consistent, high quality materials.

Larsen *et al.* [41-43] indicate that, particularly for most high performance aerospace applications, use of MMCs or other new materials will depend on life cycle cost, producibility, the range of mechanical properties which can be achieved, reliability and maintainability in service, material qualification via comprehensive testing and analysis programs, identification of a need for high reliability in extended use, and the ability to accurately predict component life. For aircraft structure such as would be used in the High Speed Civil Transport (HSCT) the drivers will be temperature (175°C at Mach 2.4 for long times, 200°C for short times)[8]; a service lifetime of 25 years and at least 35,000 thermal cycles [35]. Drag and weight are other concerns [38]. Hypersonic vehicles such as the National AeroSpace Plane (NASP)[9] have very different requirements: its uninsulated, load-bearing, hot structure was to be actively cooled with liquid hydrogen fuel [37]. Material requirements were stiffness, strength, ductility, fracture toughness, fatigue behavior and impact crack resistance, creep, density, thermal conductivity, and property retention at high temperature (skin temperatures >1650°C, speeds up to Mach 25 [40]) and, for some components, at cryogenic temperatures, and environmental resistance [41-43]. Biaxial loading was a key feature of the stiffened panels expected for the NASP skin. MMCs of most interest for primary and secondary structural applications such as skins or frames for the HSCT and sub-sonic aircraft are aluminum matrix composites (AMCs), either continuously or discontinuously reinforced; for hypersonic aircraft such as NASP, TMCs and intermetallic matrix composites (IMCs) are of particular interest. There has been some interest in the past on light weight, high stiffness, high thermal conductivity, materials for spacecraft applications such as truss structures and radiators; with the elimination of large directed energy weapons systems from the Ballistic Missile Defense Organization, formerly Strategic Defense Initiative Organization, much of the research on such MMCs (AMCs and magnesium matrix composites (MgMCs)) has been shelved. A continuous boron fiber-reinforced AMC is used for the tubular cargo bay struts in the mid-fuselage structure of the Space Shuttle orbiter vehicle [19, 52].

For HSCT engine/propulsion applications, a more likely option for MMCs at the current time, high cycle temperatures, reduced cooling flow, and higher thermal efficiency requirements imply materials with high temperature capabilities, low density, lower life cycle costs, increased durability, and repairability [35]. As an example, the HSCT exhaust nozzle requires a high specific strength material to reduce engine noise. Other materials drivers for the nozzle include extreme duty cycles and higher engine thrust which implies a high engine operating temperature - it will be at near maximum temperature for >60% flight (compared to about 2% for subsonic aircraft) [40]. For other hot structure applications such as turbine blades, material drivers include operating lifetime, high temperature and thermal shock, high cycle fatigue, and environmental resistance, especially to hydrogen-containing atmospheres [39].

Integrated High Performance Turbine Engine Technology (IHPTET) program goals, aiming to increase turbopropulsion capabilities by a factor of two over that of current technology, can only be achieved using composites [40]; it requires an integrated approach using MMCs to enable innovative structural designs and improved aerothermodynamics to achieve higher thrust-to-weight ratios and lower specific fuel consumption [41-43]. A major payoff for MMCs is expected from rotating turbine engine components using mostly unidirectional composites.

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[8] If the speed is reduced to Mach 2, temperatures will drop to 105°C and 135°C, respectively.

[9] NASP was to be an experimental hypersonic vehicle capable of taking off from a runway and achieving earth orbit with a single stage, air-breathing propulsion system [43].

Because of the high temperature required for propulsion system components most of the MMC R&D focus is on continuously-reinforced TMCs and IMCs,

In some space nuclear power and propulsion system components material selection will be driven by the requirement for a 7- to 10-year operation while generating several hundred kilowatts of power, specific strength, creep and high temperature properties, thermal fatigue, thermal conductivity, resistance to aggressive environments, reliability and durability [39, 40]. This is also true for pressure vessels, heat pipes, and regenerators. including various titanium-aluminide composites as well as more exotic reinforced superalloys.

In addition to those performance requirements identified above, automobile companies require that the material supply be stable and that there be a reasonable prospect of widespread use to spur its application in vehicles [35, 51, 53]. Allison and Cole [45] indicate their belief that there will be new Corporate Average Fuel Economy (CAFE) and emissions standards. They expect these will be achieved via vehicle weight reduction: a 10% weight reduction yields 5.5% improvement in fuel economy. The auto companies are typically looking at material substitution for weight reduction though subsystem redesign can result in additional weight savings [45, 51]. Important requirements for the diesel truck industry are more stringent EPA emissions standards which require more efficient engines. This implies higher operating temperatures and, in turn, higher temperature, stronger, lighter weight materials [34]. High materials costs can be offset by need, parts consolidation, and better fuel efficiency; but it also means a higher overall engine cost to absorb the cost of the new material[10] [34]. Primary areas of application for MMCs are powertrain/engine components, suspension and driveline parts, housings, and brake components. Material properties of interest include density, temperature capabilities, fatigue, creep, wear resistance, strength, and stiffness; others include damping, frictional properties, seizure resistance, and tailorable properties such as CTE [31, 34, 45]. The important design characteristic for drive shafts is the critical speed, the speed at which the shaft becomes dynamically unstable [45]. Specific modulus is the major material property of concern while shaft length and diameter are geometric factors. Brake rotors are driven primarily by temperature and wear resistance. Using near-net shape engine blocks and cylinder liners along with new materials can reduce gross vehicle weight: typically Al replaces cast iron. An additional 3-4.5 kg weight savings in total vehicle weight is expected to be achieved via an AMC liner to improve engine operating efficiency through improved thermal conductivity and to reduce engine friction through improved block stiffness and dimensional stability [45]. Resistance to wear, scuffing, fatigue, and creep are relevant properties; operating temperatures are <200°C. Lighter weight connecting rods and pistons are desired to reduce secondary forces that result when displacements are >2.0 liters: in this case, reciprocating masses of the connecting rod/piston assembly produce unbalanced, objectionable secondary shaking forces [45]. Using MMCs may allow engine operation at higher speed (for fuel efficiency) and higher power densities; these could lead to lower crankshaft loads and lower friction losses to decrease fuel consumption or improve performance. Critical material selection factors include high cycle fatigue at 150-180°C, CTE, elastic modulus, and wear resistance. The MMCs of primary interest for various automobile and trucking components are the discontinuously-reinforced AMCs; this is attributed in part to the significantly lower cost and relative ease of fabrication of these materials as compared to the continuously-reinforced composites.

AMCs have been used by several automotive companies already. Toyota replaced a cast iron hub of a crankshaft damper pulley to reduce weight and engine vibration [44]. Creep was a problem with conventional Al alloys. By using an AMC hub, weight was reduced by 40% and crankshaft pulley weight by 20%; engine performance was enhanced due to faster rotation. Honda uses AMC cylinder liners (chopped fiber of 12% Al_2O_3, 9% graphite) that are integrally

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[10] Using an MMC piston adds about $200 to the cost of a $15,000 engine.

cast with the Al engine block [44]. Wear depth was reduced by 2/3 relative to the Al alloy for the same weight but was the same as that of the cast iron at reduced weight (by 50%); cooling efficiency was improved. The major benefit of using MMCs for brake rotors is weight reduction which reduces inertial forces which, in turn, increase fuel efficiency [45]. The reduced inertial forces add an additional 50% to the effective mass reduction, and allow increased acceleration and reduced braking distance as well as reduced brake noise, better wear resistance, and more uniform friction over time. Composite thermal diffusivity and volume fraction and distribution of the reinforcement are critical. Duralcan has achieved a 50% weight reduction relative to cast iron on their rotors along with a factor of 3 improvement in heat efficiency, as well as reduced noise and vibration [44, 53]. These are not in full production yet but are being evaluated by automotive companies.

Drivers for new bicycle applications include weight, strength and stiffness, and riding comfort with respect to shock absorption [48, 49]. Wear resistance and weight are key drivers for bicycle disk brakes and cogs [48]. New designs - "fuselage" vs. the conventional frame - combined with material characteristics such as weldability and heat treatability will also be important [50]. As is true for many industries there is a desire to deliver products to the market more quickly. Duralcan and Specialty Bikes produce a mountain bike with an AMC frame for <$1000 [34, 53]. In another sporting goods application, Daido and Kawasaki have joined forces to produce MMC golf club heads [34].

MMCs have a potential role in electronics applications, mostly for thermal management purposes as required for electronics packaging. Electronic packaging material selection is driven by structural support requirements such as stiffness and strength and by the need for protection from hostile elements as in heat removal capabilities, CTE, and thermal conductivity [50].

One conclusion that may be safely reached upon reviewing the literature and the drivers for materials selection in these applications is an overriding concern about cost-effective, reliable fabrication processes that result in consistent, high quality materials. For a civil aircraft program, processing and manufacturing represent about 60% of total cost [35]. For advanced materials to be used in such aircraft the cost of the component must be ≤$300 per pound. The cost goal for finished automobile components is typically <$5 per pound. Recyclability and the availability of appropriate processes appear to be of increasing concern as well.

Processing

Different material manufacturing processes and fabrication procedures are typically utilized for dMMCs and cMMCs [e.g., 54-70]. A typical processing and fabrication sequence for dMMCs includes selection of the matrix and reinforcement (chopped fibers, whiskers, flakes or particles) and, possibly, a reinforcement coating. One of a number of casting [54, 56-66], powder metallurgy (P/M) [56, 66-70] or *in situ* [58, 65] processes is then selected to produce a product form. The reinforcements are randomly oriented in the composite and the material is considered to be essentially isotropic. Typical composite casting processes include sand casting, permanent mold casting, investment mold casting, expendable pattern casting, squeeze casting, die casting, pressure infiltration, spontaneous infiltration, and ingot casting. P/M processes may involve solid/liquid pressing or kinetic blending. Initial product forms may be ingots, billets, pellets, sheet, beams, slabs, or near-net shapes. These product forms can often be further worked via recasting, forging, extrusion, milling, machining, joining, or welding, though not necessarily using exactly conventional metal working techniques. Recycling process development has focused almost exclusively on the dMMCs [71].

Reinforcement forms for the cMMCs - large diameter fibers (>100 μm), multi-filament tows (<20 μm diameter fibers), or metal wires - are often coated via a chemical or physical vapor deposition process after which they are fabricated into a preform of some type and before they are integrated with the matrix material [37, 55, 56, 62-64, 69]. Preforms could be green tapes, laminated tapes, thermal sprayed tape, infiltrated wire or tapes, etc. [55]. Fiber and ply orientation are usually critical features of the cMMCs; these materials are not usually considered to be isotropic. Other processes for manufacturing cMMCs can include casting, thermal spraying, powder cloth, or foil-fiber-foil processes among others. Secondary fabrication processes for the cMMCs are much more limited: e.g., the presence of the fibers makes any deformation process such as forging or extrusion essentially impossible. Product forms are typically limited to thin-walled or sheet products or near-net shape components. As one might expect, no single process is useful for all materials.

Solidification Processes

Solidification processes offer the potential for simple and rapid, net shape production capabilities. The economics of the two primary types of solidification processes - slurry casting and infiltration with a molten metal - depend to a great extent on the viscosity of the melt. A substantial amount of the pressure required to combine the matrix with the reinforcement arises from frictional effects due to viscosity which, in turn, affect the fill rate and the capital equipment cost of the facilities required to achieve certain fill (and production) rates. Generally high viscosity materials require high pressures to achieve a given fill rate. For instance, many plastics (nylon, PEEK, polypropylene, polycarbonates) are 10^5 to 10^7X more viscous than molten metals which have viscosity similar to that of water [54], a fact which may make MMC solidification processes more economically favorable than those of some other competing composites.

The two most significant factors that influence integration of the reinforcement and matrix, especially in aluminum, are matrix wettability of the reinforcement and reinforcement/matrix reactivity. Wettability is typically defined as the "amount of work required by the metal to engulf the ... reinforcement" and is quantitatively "measured by the pressure drop at the infiltration front when the metal is entering a ... preform" [54]. Under the best and, usually, infrequent conditions, the metal "wets" the fibers and infiltrates the preform spontaneously (known as "wicking") when that pressure is negative. Application of pressure is necessary when the metal will not infiltrate the preform. Several methods of determining wettability and minimum infiltration pressures have been studied (see [94]) including simple calculations based on surface energies obtained from measurement of contact angles via sessile drop tests and assuming a reversible process; and, more recently, by a technique involving measurement of capillarity on reinforcement preforms by pressure infiltration. The growing perception is that there are two fundamental routes by which wettability of reinforcements with aluminum can be improved: methods which act to disrupt the oxide layer on the Al or promote chemical reactions between the reinforcement and Al. Specific techniques for achieving this include reinforcement pretreatment such as heat treatment; matrix alloy modifications that promote reactions with the reinforcement or that modify characteristics of the oxide layer on the metal surface; and reinforcement coatings that react directly with the matrix or that react with the oxide layer on the metal. Note that reactions may occur even when there is no wetting: e.g., aluminum reacts with graphite to form Al_4C_3. Reactions can be minimized and/or eliminated by applying non-reactive coatings to the reinforcements, usually an expensive option, or by keeping reinforcement/molten metal exposure times short by rapid cooling as in squeeze casting. Because of these problems, fiber/matrix wettability and reactivity, solidification processes for cMMCs are limited to low melting point matrices such as Al or Mg [55].

The amount of pressure required for infiltration to occur and permeability of the preform can be calculated (see [54]). Preform temperatures are usually kept low to prevent reactions. However, keeping it at such low temperatures can promote formation of solid metal at the reinforcement surface which narrows the channels for metal flow, an effect which complicates the simultaneous modeling of the process heat flow and solidification. Models of the kinetics of preform infiltration have been developed for pure metals and results have been experimentally confirmed via infiltration rate measurements. Models for alloy matrices are more complicated because the metal solidifies over a temperature range, making heat flow calculations more difficult; mass flow considerations must also be included. Permeability calculations are made more difficult by the fact that the matrix does not grow as a uniform layer on the reinforcement. While it is possible to infiltrate a preform held below the alloy liquidus temperature, macrosegregation is observed. Modeling can be further complicated by preform compressibility which may lead to noticeably higher reinforcement volume fractions.

What happens during solidification? Cooling rate and heterogeneous nucleation catalysts such as fiber or particulate reinforcements affect the nucleation rate. Nucleation rate and fluid flow, in turn, determine the grain size in the casting. If the reinforcement acts as the nucleation site the resulting grain size is often much finer, as is observed with TiC in aluminum and as may be the case for Si on carbon, SiO_2, and Al_2O_3 fibers in hypereutectic Al-Si alloys (see [54]). Smaller grain sizes can also be achieved by holding the preform below the metal liquidus temperature. In most cases, however, nucleation does not occur on the reinforcement. Grains typically grow to avoid the reinforcement since it acts as a barrier to solute diffusion ahead of the solid/liquid interface. What is frequently observed in completely solidified MMCs is a high concentration of solutes and secondary phases at or near the reinforcement/matrix interface. With slower cooling rates solid state diffusion can eliminate microsegregation. Modeling studies on the kinetics of the appropriate processes leading to homogenous microstructures have been able to predict this behavior occurs over a short period of time, about a minute for cases of commercial interest; this has also been experimentally confirmed (see [54]). Particle pushing is an important effect when reinforcements are mobile. The reinforcements are typically found in regions that were the last to solidify, resulting in non-uniform distributions.

Specific casting processes are described in more detail in the following paragraphs.

Slurry Casting and Related Processes Semi-solid slurry processes are among the most cost-effective for the production of MMCs: reinforcements are incorporated into an agitated melt to form a semi-solid slurry . The introduction of reinforcements into the melt is very crucial step in these processes; typical schemes include gas injection into a melt; pre-infiltration of a packed bed of reinforcement to form a pellet or master alloy which is then redispersed into a melt; introduction into the vortex of a stirred melt (the most common); ultrasonic dispersion; and centrifugal dispersion [54]. Not every method of introducing particles is amenable to every MMC system. The ultrasonic agitation approach, for example, helps promote wetting and better particulate dispersion but is difficult to scale to a production level. Gas porosity and particle clustering are common problems with several of the approaches.

Duralcan utilizes foundry ingot casting processes for their high volume production of castable SiC/2014 Al composites,[11] and direct chill casting and extrusion, forging, or rolling processes for their high volume production of wrought Al_2O_3/6061 Al composites [53, 54, 56, 57]. Volume fractions of reinforcement for both composite types typically range up to <0.25. In order to promote good bonding between the particle and the matrix a special, proprietary particle pre-treatment step is performed [56]. The composites are somewhat more difficult to cast than conventional aluminum alloys though, a fact which required Duralcan to develop special techniques and procedures amenable to mass production in existing equipment. Several unique properties of the molten material had to be considered [57]. The composite melt is actually a semi-solid slurry having quite different properties from molten aluminum. The fact that the SiC particles are more dense than aluminum requires that the melt be stirred to maintain a uniform distribution of particles. The SiC particles are, in addition, attracted to gas bubbles in the melt, a behavior which tends to stabilize the bubbles and could result in porosity. And, finally, the melt is less fluid during gravity casting operations due to the presence of the SiC. The fact that these slurries undergo shear thinning - melt viscosity decreases with increasing

[11] Other matrix materials may include conventional casting alloys such as A356, A357, and 380-type.

applied shear rate - makes them amenable to high speed casting processes such as pressure die casting: flow characteristics of the composite slurry appear to minimize the turbulence normally experienced by molten aluminum alloys during die filling. To help ensure an uniform distribution of particles in the final composite, Duralcan utilizes an "ice cream mixer" approach for stirring in the melt [58]. Duralcan has also developed special processes to recycle foundry-generated scrap - gates, risers, and defective castings, an important economic consideration for high volume production and, in the case of the dMMCs, a relatively expensive material (see section on Recycling and Reclamation Processes for a description). Duralcan's ingots have been successfully cast by more than seventy foundries [58].

The manufacture of the extrusion billets required special modifications to the conventional direct chill (DC) casting process as well [53, 57]. Stirring the melt as well as the rapid cooling associated with the direct chill process help assure uniform distribution of the particles in the billet [58]. A particular issue associated with the extrusion billets was the excessive die wear that occurs as a result of the Al_2O_3 particles. Finding the right saw blades capable of keeping up with the extrusion production rate was another issue. Both the extrusion die and sawing issues have been addressed such that seamless tubing, wire, and bicycle tubing are now being produced.

The presence of ceramic particles also influences welding by affecting the nature of the created weld pool. Duralcan has found that the selection of filler alloy, welding conditions, and welding method greatly influences the quality of the resulting weldment [57]. Duralcan has been able to demonstrate welding using commercial production automated methods acceptable to an automobile manufacturer: both ends of a drive shaft were welded in less than 15 seconds [53]. In addition, bicycle frames have been routinely welded. Machining techniques have also been developed: diamond tools were shown to offer a 2X to 6X improvement in tool life over conventional carbide tools even though they are more costly [45]. Note that Duralcan is the only company with a truly large-scale production capability, tens of millions of pounds per year, for manufacturing dMMCs.

Lester B. Knight Cast Metals has performed investment casting of Duralcan's SiC-reinforced composites. Claimed benefits of the investment casting process are production of complex parts having excellent dimensional tolerances and surface finishes [60]. Kennedy [59] identifies three basic criteria for demonstrating economical and practical castability of MMCs: remeltability without property degradation; amenable to standard foundry practices; and consistent and superior mechanical properties for a defect-free casting. Casting procedures are similar to those used for casting aluminum with some differences [59]. The MMC material is dried in the crucible at 390°F to eliminate excess moisture prior to melting; any tools used for skimming, etc. should also be dried. Melting under an inert gas cover atmosphere is at the caster's discretion. Formation of aluminum carbide from melt overheating can be avoided by close control of its temperature (to <750°C). A uniform dispersion of SiC particles is maintained via gentle stirring, otherwise they would sink; in addition, to prevent gas from becoming entrapped in the melt stirring is kept to a level that minimizes turbulence. In fact, mechanical properties appear to be maximized when stirring is constant (mechanical stirring) rather than intermittent [59]. After holding the molten mixture at temperature for some time, it is fluxed and degassed for about 10 minutes: conventional degassing techniques can result in dewetting of the ceramic or removal of the SiC; a rotary injection system for fluxing and degassing with an argon-SF_6 gas mixture provides acceptable results. Stirring is recommended right before pouring; minimization of turbulence is crucial to the pouring operation to prevent entrapped gas. Pouring practices are the same as for conventional aluminum alloys: keep the investment shells well-heated and the ladle lip low and as close as possible to the sprue; pour quickly, keeping the sprue full. Gating designs are important in a successful cast, again to minimize turbulence and prevent gas from becoming entrapped in the casting. Kennedy indicates that even though the composite's viscosity is higher than that of unreinforced aluminum alloys, its fluidity is nearly similar so no difference should be noted in mold-filling ability [59]. Once cast the MMCs are heat treated, typically via a solution treatment followed by water quenching and room temperature and artificial aging, to maximize their mechanical properties.

Cercast (Montreal, Quebec) has also investment-cast Duralcan billets (20% SiC in either A346 or A357 alloys) into a wide variety of products [58]. Results indicate that investment cast SiC/A357 has a fairly uniform microstructure even though some SiC and Al-Si eutectic particles are pushed into the interdendritic region. The amount formed is a function of solidification rates though it does not seem to affect tensile strength of composites cast via permanent mold, sand and investment casting [60]. Other processing constraints include avoiding mechanical stress risers by using large fillet radii or smooth transitions in casting cross-sections. In addition, Cercast recommends use of more support structures during pattern storage and heat treatment [60]. The company also works with a Pechiney composite consisting of 15% SiC particles (30 µm diameter) in A357: the large particles settle out more quickly but by controlling the solidification uniform microstructures can be produced. Apparently, they have also been able to tailor the reinforcement volume fraction within different sections of a component to enable, for example, low CTE in one region and electron beam weldability in another. This requires the use of a ceramic preform consisting of 15 to 70% reinforcement which is placed in a mold and infiltrated during casting [58, 60]. SiC particles and whiskers and chopped and continuous Al_2O_3 fibers have been used for reinforcements.

IMI (Montreal, Quebec) has developed a bottom-melt foundry process that appears to prevent inclusions of oxides and other contaminants. Molten metal is poured over particles placed in the bottom of a crucible; the metal layer acts as a seal for the bed of particles and allows a vacuum to be applied [58]. Aluminum has a high surface tension, so the buoyancy does not result in particle flotation and the vacuum can draw aluminum toward the bottom through the particles. After about 45 seconds, with sufficient degree of vacuum, argon is flowed over the metal surface and a stirrer is placed in the mixture. Use of the stirrer promotes wetting and a uniform distribution of particles, as long as turbulent conditions do not arise. Once mixed the composite can be poured into a mold and either chilled quickly for essentially isotropic properties or cooled more slowly to allow some settling of the particulate as might be required for wear resistance. This is not a production-scale process but the technology is apparently available for licensing.

Pressure Infiltration and Related Processes Pressure infiltration processes are probably among the most economic and versatile processes for producing AMCs. Primary attractions of these processes include the relatively low cost of the matrix material, reduced mechanical degradation of the reinforcement, high speed, similar tooling to that used in conventional casting; and the possibility of near-net or net shape components reducing the need for significant finishing/machining [54, 62]. Others advantages are few restrictions on matrix and reinforcement chemistry; shorter cycles and reduced reinforcement/matrix interactions due to the increase in infiltration via pressure and an increased rate of heat removal; further reduced interactions due to infiltration at temperatures below the matrix liquidus; virtual elimination of uninfiltrated parts of the preform; matrix flow through the preform to feed shrinkage areas using pressure and a properly designed cooling arrangement; and production of a refined microstructure [62]. The major identified disadvantage is that heavier tooling and other equipment may be required to force the infiltration, a potential problem for some very large or selectively reinforced castings.

Important process parameters are the initial temperatures of the preform, mold, and metal; the volume fraction of reinforcement; and the applied pressure or the infiltration velocity (which are not independent) [62]. Physical considerations such as continuity, and heat and mass conservation are used to derive the boundary conditions. Developed models of the different infiltration processes show that solutions are complex due to the inter-relationships of matrix solidification, fluid flow, heat transfer, etc., though some simplifications are possible (see references in [62]). Results generally appear to agree well with experimental data. Mortensen *et* *al.* [62] identify practical implications of infiltration physics which are include the conclusions that preform infiltration takes place irreversibly and over a range of pressures; low preform temperatures and low mold temperatures with a high pressure near the end of the cycle are desirable to minimize reinforcement/matrix interactions; high pressure should only be applied after the preform is initially filled to avoid preform deformation; the preform temperature should be above the melt liquidus when it is chemically inert to reduce segregation in the matrix; infiltration rate strongly depends on the initial preform temperature (if below the matrix liquidus) and the reinforcement volume fraction, weakly on the melt superheat; and external cooling and applied pressure determine the maximum infiltration distance.

There are, of course, more practical aspects of importance as well. Preform preparation, usually difficult and costly, can be accomplished via several methods such as slurries of short fibers followed by pressing or suction, laying up fibers in a die with a binder, or three-dimensional weaving. The achievable volume fraction is determined by the type of reinforcement and the specific preform manufacturing process selected; the maximum appears to be on the order of 0.50 to 0.60 for aligned fibers, about 0.50 for equiaxed particles of similar size, and less than 0.40 for misaligned fibers and whiskers. Many other variations are feasible and have been demonstrated [62]. Preforms are next placed in the die, along with any inserts or cores needed for part definition. Surfaces of these inserts must be such that the metal does not infiltrate it making it difficult to remove from the casting; they must also be chemically inert when in contact with the melt. Gas entrapment is usually avoided by evacuating or venting the die just prior to infiltration. Metal can be prevented from flowing into the vacuum pump when the pressure is applied by slowing melt flow via a fine porous material or by causing solidification to occur along the vacuum or venting line.

The pressure is applied either mechanically via a piston as for squeeze casting (the piston is part of the die) or die casting (the piston pushes the metal into a die) or by a gas. For some die casting processes the plunger and gate diameters are larger than would be used in a monolithic casting. The mechanically-driven systems all have large, heavy, thick-walled dies that are generally split. The dies, made of hot-working tool steels, are usually held at temperatures below the matrix liquidus (about 200 to 300°C) to avert leakage, to minimize matrix sticking, and to cause more rapid solidification. Gas-driven systems cannot operate at as high a pressure as the mechanically-driven systems; This implies slower infiltration, reduced cooling rates, and, possibly, very fine porosity. Since the die can be placed inside the pressurized gas chamber so that it is mostly in compression, other die materials such as ceramics can be considered.

Solidification shrinkage is typically handled by directional solidification combined with the applied pressure to drive the flow of molten metal to regions of the casting that are solidifying [62]. Specific techniques to achieve this depend on an understanding of thermal effects controlling solidification in the part being cast. Solidification can be inhomogeneous when the casting consists of reinforced and unreinforced regions: the composite has a different effective thermal conductivity and heat capacity and a reduced volumetric latent heat of solidification compared to the matrix; the matrix solidification path may differ as well due to the presence of the reinforcement. Using a porous insulating lining at the mold walls can help control heat extraction through cold walls in a mechanically-driven system: before infiltration it acts as an insulator and after infiltration it acts as a high conductivity path for rapid heat flow into the mold. The basic process has been adapted for continuous casting of MMCs. For example, using techniques similar to those that prevent metal flow into the vacuum pump or venting system and moving the preform relative to the die so that such a seal would be sustained can allow continuous production. Centrifugal casting is another approach which eliminates two difficulties with the aforementioned process: potential friction at the matrix seal and high stresses in the preform leading to breakage. In this case a body force rather than a hydrostatic force pushes the matrix in one direction into the preform. MIT researchers have developed and demonstrated another process which relies on fluctuating magnetic fields that induce eddy currents in the melt which, in turn, interact with the magnetic field to create a Lorentz force in the melt, projecting it into the preform [62].

Alcoa has made use of a pressure casting approach to fabricate net shape components utilizing Duralcan billets (15 to 20% SiC) as well as materials containing 55 to 60% SiC [58]. The process was thought to offer low cost and improved properties relative to die casting approaches. It does result in superior surface finishes and quite good dimensional tolerances such that machining and other finishing steps may not be necessary. This is desirable for high volume applications [45].

The Japanese have investigated a gas pressure infiltration process as well [61]. The preform may consist of woven structures or tape layups, usually used for large diameter stiff fibers, which can be oriented to achieve the desired properties. The application of pressure forces matrix contact with the reinforcement - a mechanical bond forms between the two - and eliminates the wetting difficulties noted in other processes.

Squeeze casting is another variation on pressure casting: it is a simple mechanical pressure casting process involving placing a heated preform in a die, introducing the molten metal over the preform, and a bringing down a mechanical press of some sort (like a forging press) to force the liquid metal into the preform [54, 63, 64]. The high pressures used during solidification help to achieve castings with improved properties and reduced or eliminated defects. In general, the process is believed to be economical and efficient with potential for automation, important in high volume applications. Achievable pressures using large forging presses are on the order of 50 to 100 MPa but equipment and tooling are expensive and production rates are not high [54, 64]. Using smaller presses allows reasonable pressures, about 15 MPa, and higher production rates to be achieved. Heat- and fluid-flow modeling results indicate there are a number of factors which influence the threshold pressure, rate, and depth of infiltration: fiber volume fraction and size, preform and melt temperatures, operating pressure, infiltration speed, and exothermic effects arising from any preform treatment [64]. The threshold pressure is only a few atmospheres but the pressure required to eliminate porosity and interfacial voids is several orders of magnitude higher. Another positive feature of this process is attributed to isothermal, partial remelting of the composite which causes the initial matrix dendrites to transform quickly into globs such that the resistance of the slurry to deformation is significantly reduced [64]. Other secondary forming processes using less complicated equipment can then be used to produce the final part shape at lower cost. For large-scale production of MMC components, careful process control will be necessary. Important variables include fiber and melt preheat temperatures, metal alloying elements, external cooling, melt quality, tooling temperature, the time lag between die closure and pressurization, pressure levels and duration, and plunger speed. Other key features critical to actual component design include die design to minimize direct die/melt contact, designs to promote fast infiltration with minimum segregation, and three dimensional fiber architectures that provide preform resistance to deformation at high pressure and temperature and prevent fiber misalignment. Preforms should also be designed to provide the necessary performance at the lowest possible fiber volume fraction to keep costs down. Degassing the ceramic slurry for the preform after agitation appears to improve the fracture strength of the composite by a substantial amount, 26% [64].

Westinghouse has been developing a centrifugal casting process. In this process, a mixture of particulate and molten metal is poured into a mold rotating at several thousand rpms [58]. The outward forces on the particles can be controlled via the rate of rotation. For instance, an alloy containing 10% SiC can be cast such that the outer layer contains 25% SiC. Changing the particle size or, even, the particle type/composition allows further tailoring of the composite: heavier particles would be concentrated toward the outer edge of the cylinder, lighter particles toward the inner edge [58, 61]. Important process parameters are density differences between the particles and the melt, mold size, and pouring temperature [61]. Westinghouse demonstrated the process by casting 4-in diameter x 12-in length tubes with controlled microstructures.

Thixomolding is the tradename of a process developed by Thixomat for MgMMCs. Thixotropy, a physical state in which liquids and solids co-exist in a low viscosity slurry, is produced when shear stresses are applied to an alloy heated to just below the liquidus temperature [58]. A barrel holds the reinforcement particles, usually SiC, Al_2O_3, or B_4C, and apparently semi-solid matrix alloy pellets (AZ91D); the advancing high temperature screw shears the materials, making a semi-solid slurry which is then forced into a die at high velocity (20-50 μsec/shot) and pressure (6 ksi) [58]. The mold is filled by the mixture in the semi-solid front mode such that lower porosity and shrinkage than for conventional liquid metal casting are observed. Particle distribution is also claimed to be good. Being able to eliminate a separate melting operation and its associated material loss results in a lower cost process. Since temperatures are below the liquidus longer die life is expected along with increased productivity. These parts can also be heat treated due, in part, to the reduced porosity. This is apparently a production process for monolithic Mg components but not yet for composites.

Lanxide has developed a pressureless infiltration process (Primex®) in which an ingot of aluminum alloy is placed in contact with a ceramic preform, typically SiC or Al_2O_3 particulate [58, 65]. Two features known to be important are an alloy containing 3 to 10 wt. % Mg and a high temperature nitrogen atmosphere. Under these and other proprietary process conditions the ingot melts and spontaneously infiltrates the preform. Reinforcement volume fractions can be quite high, approaching 0.50 or more. The process has been used for near-net shape structural parts, thermal management components, and electronic packages.

Powder Metallurgy and Related Processes Powder metallurgy techniques are used by a number of firms including Advanced Composite Materials Corp. (ACMC) and DWA Composite Specialties. The patented ACMC process involves pre-alloyed aluminum powder mixed with SiC whiskers or particles. This powder mixture can then be hot-pressed into billets over a range of sizes, ~1.5 to 100 kg [56]. The particles result in more isotropic properties while the whiskers result in more directional properties. In any case, fracture toughness and ductility in the composite are controlled by the matrix alloy composition and temper; modulus and tensile strength are controlled by the reinforcement. The billets can be machined, extruded, forged, etc. using fairly conventional methods. The composite, referred to as SXA some years ago, is available in structural, instrument, optical, and electronic grades. The structural grade requires single crystal SiC whiskers and was claimed to be useful for various space structures. Volume fractions are higher, about 0.35, though for critical man-rated structures it was thought a volume fraction of 0.15 and a modified matrix alloy would be required. Tubes (0.35 SiC/2024) and large sheets, up to 0.25-cm thick x 1.8-m wide x 6.1-m long have also been fabricated. Thermal expansion, conductivity, and density are important material characteristics for the electronic grade. Volume fractions of SiC in these grades range from 0.30 to 0.40; elemental Si (0.15 to 0.25) is also added. The instrument grade contains 0.35 SiC particulate in 6061. The optical grade is a modification of the instrument grade and contains a reduced particle size distribution, an increased dispersed oxide content, and optimized precipitation; stress relief procedures are also utilized. ACMC's production capabilities in 1989 were 20,000 kg/year for billets ranging in size from ~1.5 to 100 kg [56]. At the time they planned to scale up to 68,000 kg/year with an increased billet size of ~300 kg.

Krishnadev *et al.* [66] have investigated and compared several P/M processes - mechanical alloying and conventional dry mixing - as well as an ingot metallurgy approach for making SiC/Mg composites. For the mechanical alloying approach, 50-63 μm-diameter powders of pure Mg were mixed with 6 μm-diameter SiC particulate (10 to 30%) in a rotating ball mill using chromium-steel balls; mixing was carried out in a dry argon atmosphere for 7 hours. The resulting products were miniature SiC/Mg powders which were hot pressed and hot extruded (16:1 ratio). For the other P/M process the powders were mixed for 4 hours in a simple ball mill to obtain uniform mixing of the powders without SiC incorporation into the Mg; these powders were then hot pressed and extruded as for the other powders. Cast composites were manufactured using either pure Mg or a Mg alloy with 10 and 15% SiC; the SiC particles were 24 μm in diameter. The Mg and Mg alloys were melted under a controlled atmosphere of dry CO_2 to prevent contamination and reduce inclusions; preheated SiC particles were added while the melt was being stirred. The cast rods were homogenized and then extruded (about 20:1). The mechanically alloyed material generally exhibited better yield strength, ultimate tensile strength (UTS), and ductility than the conventional dry-powder mixed material due to greater microstructural refinement and uniformity and good adhesion between the particle and matrix; it also exhibited better properties all around than the cast material. Problems were noted when volume fractions of SiC were ≥0.30: a process control agent of some sort to improve distribution of SiC during mechanical alloying is thought to be necessary. Examination of fracture surfaces showed no particle cracking: cracks were observed at particle/matrix interfaces and in the matrix around particles. The cast material exhibited higher modulus and yield strength but dramatically lower ductility. Deformation appeared to be much less than in the other materials perhaps due to the large size of the particles, coarse microstructure, and an apparently weak bond between the particle and matrix.

Dynamet has developed a TiC particle-reinforced Ti composite (CermeTi) using a P/M approach that combines Cold pressing and Hot Isostatic Pressing (CHIP) [67]. The process involves cold isostatic pressing of blended powders - e.g., Ti, alloying elements, master alloys - in a reusable elastomeric mold to compacts having fairly uniform densities of 80 to 85% of theoretical; this is followed by vacuum sintering to 95% theoretical density and HIPing to 100% theoretical density. Costs are projected to be reasonable due to the relatively low cost of the raw materials, the fact that additional canning is not needed for the HIPing step, and the fact that complex parts can be made near-net shape. The composites can also be extruded and forged. Properties appear to be equivalent to or better than those of conventional cast or wrought parts made from the monolithic materials: improved strength and stiffness properties at temperature, better creep- and stress-rupture behavior, similar fatigue, fracture toughness, and ductility. These composites can also be very easily diffusion bonded to a monolithic alloy having the same composition as the matrix (a micro-/macro-composite), thereby providing added flexibility for composite design via selective reinforcement.

Pacific Northwest Laboratories [68] examined several rapid solidification approaches - atomization and melt spinning of ribbon and flake forms - for making discontinuously-reinforced SiC/Mg alloy composites. As one might guess advantages include refined microstructures, better compositional uniformity, a high degree of supersaturation, retained metastable phases, and, often, improved properties. Pacific Northwest selected melt spinning of flakes - sizes are about 6 mm x 8 mm x 40-60 μm - as the most promising approach: the flakes can be directly consolidated via extrusion, forging, rolling, etc., without additional size reduction, as would be required for melt-spun ribbon, or without powder blending and vacuum hot pressing steps, as would be required for conventional P/M techniques, thereby leading to lower costs. Critical process parameters are quenching wheel speed - too fast a wheel results in too thick flakes, too slow, no flakes - and the amount of material impacting the wheel - functions of the crucible orifice diameter and pressure applied to the crucible. Properties of the melt-spun flake material were better - higher tensile yield strength (TYS) and UTS and much higher tensile elongation than either the ingot or P/M material. Property improvements in a SiC/A356 Al alloy composite and Allied Signal's SiC/5090 Mg alloy composite were also noted using this melt spinning approach.

Another rapid solidification spray process is the Osprey process [69]. Molten metal is directly atomized and spray formed onto a mandrel in this process. Throughput can be considerable, on the order of hundreds of kg/hour, but since particle velocities are low deposit densities can also be low. Secondary processing such as hot pressing is often required.

Plasma spraying is basically a two-step process involving disintegration of a molten metal into very small, micron-sized solid, liquid, and partially solidified droplets that are deposited onto a substrate surface which may or may not contain reinforcements [55, 70]. The molten metal is energetically decomposed into droplets either via inert gas jets or plasmas. It is attractive for the following reasons: extreme heat removal efficiency during atomization, relatively low processing temperatures which limit segregation and coarsening phenomena, minimal surface oxidation and other detrimental reactions due to the inert gas, its ability to be used for near-net shape processing or for deposition of difficult-to-form materials, and increased safety due to reduced handling of fine particulate. Throughput can be quite large, on the order of 5 to 30 kg/hour depending on the material and desired characteristics of the product. Fiber spacing uniformity is usually better than that obtained from the foil-fiber-foil process, described below [55]. Vacuum plasma spraying is important for depositing materials that undergo reactions with oxygen [69]. High velocities which result in greater particle flattening and lead to increased density are also typical as are higher process temperatures (>800°C) which result in stress-relief annealing which, in turn, reduces residual stresses. The process has been utilized to deposit a wide variety of dMMCs and cMMCs as well as IMCs (see [69]). The plasma spraying process is also used to deposit titanium and titanium aluminide preforms which are then cold rolled to produce foils used in making TMCs via the foil/fiber/foil process. The primary limitation of the process is that it is line-of-sight. By using multiple computer controlled guns, it is possible, at least in principle, to form complex shapes.

Textron has fabricated composites using their SiC monofilaments in aluminum for potential aircraft applications. The process to make a ply involves wrapping 6061 foil then SiC fiber around a drum followed by plasma spraying of the aluminum such that the volume fraction is about 0.50 SiC. The plies can be stacked in the desired orientation and thickness, molded to net shape, and hot isostatically pressed. This material is considered developmental and is, therefore, not manufactured in production-scale quantities. Under the NASP program, GE used a plasma deposition process: rapidly solidified Ti alloy powder was sprayed onto SiC fibers to make monotape - a single layer of fibers surrounded by matrix material [37].

In Situ Processes Some of the more innovative methods of producing discontinuously-reinforced composites are those involving *in situ* production of the reinforcement phases. Better control of the size and volume fraction of reinforcement is possible; in addition, the reinforcements are often more thermodynamically stable since they nucleate and grow from the parent matrix. The size and distribution of reinforcement phases can be controlled using knowledge of local mixing laws and by suitable selection of the matrix, the reacting phases, its concentrations, and its reactivities. Controlling the melt through careful alloy design and the reaction chemistry allows one to form a number of different carbides, nitrides, oxides, borides, or silicides, or even combinations of them; potential reinforcement phases being considered include TiC, TaC, B_4C, SiC, Si_3N_4, and BN with conventional metal matrix materials such as Al, Ni, Cu, or Mg as well as with higher temperature nickel and titanium aluminides. Specific *in situ* process methods include liquid-gas reactions, liquid-solid reactions, mixed salt reactions, directed metal oxidation/nitridation reactions, reactive spray forming, self-propagating high-temperature synthesis, liquid-liquid reactions, and plasma reactive synthesis. A brief summary of each process follows [65]:

Liquid-gas reactions: The reinforcement phase results from gas injection into a reactive liquid nonferrous metal. A fine dispersion of refractory particles is produced via reaction of the gas and the solute alloying elements. Advantages include fine reinforcement size, good reinforcement/matrix interfaces, economical processing, thermodynamic stability, continuous processing capability, chemically clean process, rapid formation kinetics, and a net shape manufacturing capability. Disadvantages include low volume fractions and limited reinforcement options, high processing temperatures and melt viscosities, and reinforcement segregation.

Liquid-solid reactions: This is the basis for Martin Marietta's XD™ process (see also [37, 58]). Basically, the ceramic phase reinforcement precipitates in the molten matrix via diffusion of the components. An example would be formation of TiB_2 in aluminum: elemental or alloy powders of Al, Ti, and B are melted and Ti and B diffuse and precipitate out as TiB_2. Particle sizes are small, on the order of 0.1 to 3 μm, and interfaces are reported to be clean and stable which should result in improved properties. Often, the solvent matrix is combined with a high volume fraction ceramic "sponge" to produce a composite with a higher reinforcement content. Second phase particle distributions and shapes are tailorable; a mixture of different distributions, coexisting sizes and shapes, and/or reinforcement types can also be achieved. The dispersoids, mostly stable, can survive remelting and can be worked into other forms. Martin Marietta is working composites such as A201-XD (15 to 20% TiC) [58].

Mixed salt reactions: This process has been specifically developed from a process to make grain-refining alloys for the aluminum industry. Mixed salts of titanium and boron react in molten aluminum to form TiB_2; by-products are removed and the boride-containing alloy is cast into waffles or ingots. The London Scandinavian Metallurgical Company claims particles are about 1 or 2 μm; yield strength, elongation, and modulus of a 2014 composite are 500 MPa, 5%, and 90 GPa, respectively. There is some uncertainty about the particle/matrix interface due to the salt reactions and possibility of contamination from the reaction by-products.

Directed metal oxidation/nitridation: Lanxide developed this Dimox® process in which molten metal is exposed to oxidizing atmospheres at relatively high temperatures. The oxide reaction product grows toward the oxidizing atmosphere via capillary forces which wick the molten metal to the surface. The presence of Mg and Zn in the aluminum help provide wettability of the oxide and promote wicking by altering the surface energies of the melt. The end product consists of fine channels of metal alloy in a three-dimensional, interpenetrating network of oxide. A filler such as SiC can be used to make a three-phase composite as long as the filler is stable at the high process temperatures and can wet the metal to help in wicking. Some of these composites, such as the 50 to 70% SiC/10 to 20% Al/Al_2O_3 may be more properly categorized as ceramic composites due to the high volume percentage of ceramic reinforcement. This process is amenable to near-net shape manufacturing and is projected to be cost effective for applications like electronics packaging or valves.

Reactive spray forming: This process is fairly new and has been demonstrated for intermetallic composites: Ni-Al-B-Y melt was atomized in an N_2-O_2 gas mixture forming a product of Ni_3Al with some Y_2O_3 and Al_2O_3 dispersoids. It is thought that a variety of composites could be synthesized by carefully selecting the alloy additions and the atomizing gas based on thermodynamic considerations. An advantage of this process is the ability to form near-net shapes.

Self-propagating high temperature synthesis: This technology, developed in Russia, has similar advantages to those of the liquid-gas reaction processes except that reinforcement volume fractions can be high and control of reinforcement size and shape, porosity, and process cleanliness may be issues. The raw materials for the process are elemental powders. Process viability for making carbides, borides, silicides, nitrides, and hydride- and oxide-reinforced MMCs has been demonstrated.

Liquid-liquid reactions: Sutek Corporation practices the Mixalloy process in which two or more, high speed, turbulent metal streams react to form the particulate reinforcement. The resultant, apparently still molten mixture can be cast in a mold or rapidly solidified via atomization or melt spinning. This process has only been demonstrated for TiB_2/Cu MMCs.

Plasma reactive synthesis: High thermal energies obtained from plasmas are utilized to create reactive chemical species/reinforcement precursors in the presence of heated vapor, liquid, and/or solids with this new process approach. Plasma temperatures in these processes are quite high, over 10,000 K, a temperature range at which melting and reactions occur between most materials, with the right thermodynamics and kinetics. It has been demonstrated for Al with AlN, Al_2O_3, or SiC; NiCrTi-base alloys with TiC or TiN; and intermetallics with oxides, nitrides, borides, and/or carbides. Quality and uniformity of the products are claimed to be of "metallurgical grade" (which may mean comparable to materials produced by more conventional metallurgical processes such as casting); particle sizes are on the order of 0.005 to 5 μm.

Other Deposition Processes Chemical vapor deposition has also been considered for some aspects of cMMC fabrication. In these types of processes, a gas phase reacts with other vapors in the vapor phase (homogeneous nucleation) or at a hot substrate (heterogeneous nucleation) to form coatings over a range of thicknesses and, under some conditions, with varying composition. Process temperatures are usually quite high, to 1100°C for metals. The short mean free path leads to excellent throwing power which allows for chemical vapor infiltration of porous materials [55]: this is important in coating fiber tows containing large numbers of fibers and well as preform infiltration. Fibers are typically less damaged and porosity can be lower than for liquid infiltration methods. However, long process times are usually required and the matrix materials that can be deposited are limited to those which are simple - no solid solutions or ternary oxides - and have gaseous or liquid precursors; capital costs are also high [55]. Gas flow is an important process parameter; handling of corrosive/toxic gases and liquid feedstock are special problems. The use of CVD processes for MMCs has generally been limited to fiber coating - no matrix deposition.

A chemical vapor deposition (CVD) process is combined with fluidized bed processing to manufacture W-reinforced niobium composites for potential use in space nuclear power systems [39]. In this process a coating alloy is blown through a porous bottom slab of a container filled with metal powder; a chemical reaction takes place to give uniform coatings on each particle; the final steps appear to involve sintering and, possibly hot pressing to promote full consolidation. The result of the CVD/fluidized bed approach is a shorter sintering time, reduced grain growth, and improved toughness, strength and fatigue properties.

Various hot pressing processes combined with other processes are also used to manufacture MMCs, typically for the high performance cMMCs. For example, high conductivity/high modulus graphite fibers have been combined with Al for thermal management applications [54, 56]: the graphite fiber tows (P-100) are coated with TiB (CVD) to promote wettability, then drawn immediately through a molten bath to form a wire (infiltration); the precursor wires are then laid up flat and in parallel using a fugitive binder; the stack is heated under vacuum to drive off the binder and can then be hot pressed, hot rolled, or pultruded for final consolidation. Note that the TiB coating is not air-stable so the coated tows can not be exposed to air. Sizes that can be fabricated using this approach have been rather limited though individual plies could be oriented to produce anisotropic or quasi-isotropic in-plane properties. None of these high performance graphite-reinforced composites have ever been produced in any significant quantity; batch-to-batch quality and quality within single panels are extremely variable. This process has also been demonstrated using other materials (see [54, 55]).

The solid state foil-fiber-foil process has been one of the most widely used for the production of TMCs: layers of metal foil are alternated with typically unidirectional fibers in the form of mats; degassing and vacuum sealing; hot pressing or HIPing; and can removal followed by final machining, etc. [55]. The foils, when they can be obtained in the appropriate composition and size and thickness, are usually quite expensive. In addition, many of the alloys of interest are difficult to work and are, therefore, not available in foil form. The mats can be produced by cross-weaving fibers with a metal wire or ribbon or by using a binder, which is driven off during the degassing step, to held them together. A variation of this process, the powder-cloth process, uses a "cloth" of matrix produced by rolling an alloy/organic binder mixture with the same fiber arrangement; the binder is again driven off during the degassing step. With these types of fiber arrangements and matrix forms the processes appear to be most suitable for flat products. There may, however, be equipment constraints on the size of articles that can be pressed (pressing capacity) and diffusion bonded (pressure requirements) [55].

Some researchers have been developing physical vapor deposition (PVD) electron beam evaporation and magnetron sputtering processes for depositing matrix material [55]. Magnetron sputtering sources are somewhat more suitable for coating fibers because they can be made in various shapes (planar, curved, cylindrical) and can be positioned in different ways (vertical, horizontal, facing up or down). However, their deposition rates are low - on the order of 1 to 5 µm/min - while those for high power e-beam guns can be quite high - up to 3000 µm/min [55]. The sputtering process produces higher energy condensing species than the e-beam process does. Consequently, higher thermal stresses can result and deposit microstructures can be affected. Both processes can be quite inefficient in terms of energy and source material usage; capital costs are likely to be substantial as well. Large diameter SiC fibers have been precoated with a thick layer of matrix material prior to consolidation using the e-beam process. It is claimed to offer potential for lower cost MMCs since expensive foils, powders, or wires are not required; however, it brings along its own set of costs. One advantage of this process is that each of the fibers is completely coated so that during handling (lay-up, etc.) the possibility of damage to the interface coating or the fiber itself is reduced. The achievable volume fraction in the composite is determined by the thickness of the coating layer: it is possible to obtain volume fractions as high as 0.80. Fibers appear to be fairly uniformly spaced, too. And since binders are not neccesary there is no chance of contamination from the binder decomposition. Some research suggests that these fine-grained matrix-coated fibers can be consolidated under superplastic conditions (see [55]). Partridge and Ward-Close [55] claim these coated fibers are also suitable for net-shape processes but that remains to be proven, especially when very stiff, large diameter fibers such as SiC are used.

Recycling and Reclamation Processes Some in the automotive industry and other users are beginning to think in terms of life cycle costs and how to analyze them [45, 72]. Though not in practice at the current time, many believe this concept will develop as a result of regulatory pressures. The Japanese have already embraced the life cycle concept for their automobile industry: 6% of discarded cars were recycled in 1970; this number increased to 63% in 1980 and 95% in 1985 [73]. This philosophical change for the rest of the world will require cradle-to-grave thinking, thinking which implies front-end planning related to the design, manufacturing, life-cycle, use, and disposal of products [73, 74]. Part of this thinking includes consideration of toxicity issues, health and safety, service life, the recycled content of manufacturing material, reuse and recyclability of products, energy use, manufacturing wastes, and disposal alternatives. The issues associated with recycling and reclamation are of concern to the MMC industry since the ability to recycle and/or reclaim these materials is likely to affect their use. Processing efforts so far appear to be focused solely on process-generated scrap from the dMMCs, especially the SiC- or Al_2O_3-reinforced aluminum composites, rather than end-of-life component scrap. Recycling is a complex problem [19, 71]: leaving the reinforcement in during remelting may result in contamination via formation of undesirable reaction products. Reinforcement/matrix reactions occurring during the recycling operation may also make the reinforcement unsuitable for reuse or reclamation. It is likely that some NDE methods may need to be developed specifically for segregating acceptable MMC scrap from that which is not. Once MMC components are integrated into real systems with components fabricated from many other materials other NDE tools may be needed to determine acceptable scrap [19].

The scrap value of a dMMC is highest when the material can be recycled into a composite having the same properties as the original (recycling); but when the impurity content becomes too high for further recycling, the individual components, aluminum and reinforcements, may be recoverable (reclamation). Recycling processes for Duralcan's wrought (e.g., 6061) and foundry materials (e.g., high Si content alloys) are different. Three major forms of recyclable scrap are generated for 6061 wrought alloys [71]: direct-chill cast log ends (about 10% of length) which are the cleanest, most controlled, and recyclable of the wrought scrap; extrusion butts and light extrusion cuttings (25-30% of total extrusion billet weight) which must be segregated and controlled. Schuster *et al.* [71] performed four recycling runs on a 20% Al_2O_3/6061 composite using 100% scrap. The process steps include melting the scrap followed by stirring to keep particulate from settling and to ensure an even distribution in the cast product; this is followed by a direct chill casting process and other secondary processes such as extrusion. The alloy chemistry and particle content were found to be about the same. The alumina particles are not thermodynamically stable in the melt, however: the spinel phase ($MgAl_2O_4$) about 3 vol. % total), formed by reaction with the alumina, was observed on particle surfaces [71]. Values of tensile strength and fracture toughness of subsequently extruded/heat-treated materials were not affected, though. While 100% scrap was used in the study the authors felt that 25% scrap mixed with virgin material was most practical [71].

The process for foundry materials - typically SiC particles in a high Si-content aluminum casting alloy - requires foundry returns such as gates and risers for scrap. SiC is not thermodynamically stable in the aluminum. The aluminum carbide reaction product degrades fluidity of the molten MMC and affects composite resistance to corrosion as well as mechanical properties [71]. This reaction can be reduced by controlling temperature, time and Si content; there is no reaction when the Si content is ≥9wt.%. Cleaning and degassing steps may be required as part of the process; it depends on the quality of the scrap in terms of oxides, hydrogen gas, and other impurities in addition to the quality required for the recycled material. Duralcan has developed an eleven-step process involving virgin and scrap MMC material, melting and skimming dross under an inert gas environment; melt agitation to prevent SiC from settling and to ensure uniform distribution upon casting, fluxing, sitting time (without stirring), and skimming again followed by a short period of agitation before casting [71].

Reclamation can be accomplished with material that can't be recycled unless it is contaminated or low-grade scrap containing excess Li, Fe, or other elements or alloy impurities. Particles can be removed by common salt or fluxing techniques similar to the techniques used to remove impurities from aluminum alloys [19, 71]. The success of the process hinges on effective dewetting of the particles from the aluminum, SiC being more difficult to dewet than Al_2O_3. Reclamation process steps are as described [71]: salt is incorporated into the melt via the addition of a solid mixture of salts or via injections of quantities of reactive gases; a salt film forms at the surface of a gas bubble; as the number of bubbles increases, the probability of particle/bubble contact and, therefore, the probability of particle removal, increases; the salt phase wets the particle which is absorbed at the salt/metal interface or directly into the salt phase (dewetting, 10-20 minutes); after contact the particle then floats to surface. An agitator system is also required, at least for the Duralcan materials. On some trial runs, the resulting aluminum alloy quality was found to be good, no apparent contamination [71]. Alcan researchers performed several large scale trials with large quantities of extrusion and foundry scrap material (~3k to ~10k kg) using a rotary salt furnace [71]: about 80% of the aluminum from Al_2O_3/Al composites was recovered, a little less when the material contained SiC reinforcements. The resulting salt cake product, skimmed from the top and containing the reinforcements, is treated as waste. Reasonably good, cost-effective techniques for reclaiming the reinforcements do not appear to have been developed yet.

Several conclusions can be clearly drawn from these process descriptions: (1) no single process will fit every application; (2) while a large number of processes have been developed for the fabrication of MMC materials and components, few may be considered to have reached a production level; and (3) there are a number of technical issues to be addressed.

Technical Processing and Related Issues

A number of technical issues, some applicable to both dMMC and cMMC processing, have been identified in the literature. These issues and their effects on other properties are briefly described below. Note that mechanical properties and related subjects are not discussed at length in this section except, perhaps, to provide an indication of the importance of processing and pertinent issues with respect to them; see [e.g., 75, 76] for more detailed presentations of this subject matter.

Issues associated with reinforcement/matrix chemical reactions, reinforcement distribution, CTE mismatch, and processing defects and damage are particularly important because of their impact on mechanical and physical properties [e.g., 37, 40-42, 54-56, 60, 44, 77-86]. Properties of the MMCs produced so far, particularly the cMMCs, are quite variable in terms of strength, corrosion and oxidation resistance, thermal stability, creep strength, thermal cycling sensitivity, low toughness, and scatter in toughness values as a result of these aforementioned issues [55].

The interface is probably one of the most important features in a composite system: it affects mechanical properties through debonding, damping, crack deviation, and grain boundary pinning [77]. Reinforcement/matrix interface issues figure predominantly among the identified problems for both dMMCs and cMMCs [37, 40-42, 54-56, 60, 64, 77-82, 84]. While some reactions at the interface may be desirable it is typically not the case. Chemical reactions which degrade the reinforcement/matrix interface have been a particular problem for high temperature cMMCs. Interface reactions in titanium-aluminide composites developed for NASP were observed to occur at the consolidation temperature [e.g., 37, 40]. Reactions between the fiber, matrix, and cross-weave materials have been observed in MMCs produced via foil-fiber-foil processes [55]. These reactions have been observed in superalloy and refractory-based MMCs as well as TMCs [40]. DeKock and Chang [78] identify three types of interfaces: Class I in which the reinforcement and matrix are non-reactive and insoluble; Class II in which both are non-reactive but soluble; and Class III in which both are reactive and form at least one new compound at the interface. They indicate that Class II or, possibly, Class III systems may be acceptable if maximum service temperatures are limited or if appropriate protective coatings are used. Efforts to prevent these reactions from occurring usually consider various forms of protective coatings, reduced processing times, temperatures or pressures, or matrix alloy additions [e.g., 77-80].[12]

Constitutive behavior of the composite is greatly affected by reinforcement distribution and spacing. Variations in reinforcement spacing can give rise to high local stresses and to local shear zones. In some cases, when reinforcements are touching, a crack may form, partly as a result of thermal residual stresses, partly as result of there being no metal there. Cracking appears to increase with decreasing fiber spacing, particularly at <30 μm [55]. Rule-of-mixtures strength properties are often not achieved in the cMMCs, particularly when the matrix materials exhibit low ductility. This is attributed to poor fiber distribution, as well as to porosity, matrix foil contamination, and thermal residual stress cracking. Rohatgi [64] suggests that strength variability can be addressed in part via using a hybrid fiber approach with continuous fibers, whiskers, and particulate mixed together: it apparently prevents fiber-to-fiber contact and causes

[12] Warrier and Lin [80] developed a rapid infrared forming (RIF) process for the fabrication of TMCs with the goal of reducing the processing time at temperature. In this process the alloy and fiber are heated via an IR furnace in an Ar atmosphere. Selective heating of the crucible and composite due to different IR absorption characteristics allows for fast heating rates, as high as 200°C/sec. The composite, up to 8 plies thick, can be processed in a few minutes rather than a few hours. Reactions do occur but the short process times considerably limit the amount of reaction product that forms.

detrimental intermetallic phases to nucleate on the whiskers and particles rather than on the fiber/matrix interfaces. Near ROM strengths can be achieved.

The distribution of the reinforcement in the final product has also been noted for both slurry and pressure casting processes. In the dMMC slurry casting processes, in particular, the particles increase viscosity of the melt so that stirring is needed to prevent particle settling and promote homogeneous distribution [45]. Control of melt temperatures, stirring methods and rates, degassing, and filtering are deemed critical to achieving good, consistent quality material and/or components. The slurry mixture is difficult to degas due to the potential for trapped gas at the particle/melt interface which gives rise to porosity [56, 60]. The reinforcement distribution problem is exacerbated by the fact that at slow solidification rates particles are pushed ahead of the solid/liquid interface by growing dendrites such that rings of particles are often observed surrounding the grains [68]. This "particle pushing" by dendrites during casting may be a serious problem, in some cases resulting in severe agglomeration and interparticle contact. Research indicates that when reinforcement sizes are very fine in dMMCs, clumping occurs which implies non-uniform distribution. Coarser particles can lead to particle cracking and fracture [85]. This behavior would seem to indicate an optimum particle size. Dumant *et al.* [60] observed that fracture occurs between particle clusters and Al-Si eutectics in the interdendritic region of a cast SiC/A357 composite: cracks grow through adjacent clusters and meet causing macroscopic failure. This has also been seen in other alloys [64, 83-85] and is the most commonly observed failure mode: damage occurs via particle cracking and failure occurs when these damaged areas link up, primarily through particle clusters. In other low strength, low volume fraction or small particle or P/M composite material systems, the particle separates from the matrix before the damaged areas link up [84]. Important factors are dendrite arm spacing in the matrix, reinforcement size, relative thermal conductivities of the reinforcement and matrix, and the difference in contact angles between a particle/liquid and particle/solid interface [64]. It appears that the presence of fibers accelerates coarsening kinetics of the matrix.

In pressure casting processes, the metal tends to form channels during infiltration due to poor reinforcement/matrix wettability and metal viscosity so that the reinforcement is concentrated into regions of high volume fraction surrounded by channels of unreinforced metal. To prevent this channeling effect, one is limited to fabricating composites of maximum volume fractions of 0.55 to 0.60 for fibers and about 0.30 for particulate [54]. This volume fraction limitation somewhat reduces the flexibility in tailoring properties. But reinforcement-to-reinforcement contact lowers transverse strength due to stress concentrations and poor infiltration at the contact points; sintering of fibers or particles can also occur at these points and may, in fact, promote particle clustering seen in slurry casting processes [54]. Shrinkage porosity due to insufficient infiltration may arise in pressure casting processes when the preform is not properly vented [54]. Partridge and Ward-Close [55] note highly variable fiber spacings, porosity content, and number of fiber-fiber contacts in cMMCs fabricated using melt infiltration methods. Hydrogen pickup, reinforcement contamination, and oxide inclusions are other problems associated with the cast aluminum MMCs [45, 56, 60, 64]. Rohatgi notes that imperfect control of important process variables in squeeze casting results in freeze choking, preform deformation, and other common casting defects [64]. The spatial distribution of reinforcement can apparently be improved by secondary processing such as hot rolling, swaging, or extrusion [84].

Reinforcement distribution is an issue with P/M processes as well. It arises from differences in reinforcement and matrix powder sizes [68]: reinforcement diameters are on the order of 5 μm compared to matrix powder diameters of 20 to 40 μm. This large size difference can lead to non-uniformities in composite microstructures: small reinforcement particles congregate around larger matrix grains. The optimum size was determined to be 10 to 15 μm [68]. If the starting powders are heavily oxidized very fine submicron oxides are observed at grain boundaries; their presence reduces fracture toughness.

While the *in situ* processes appear to be attractive from a cost perspective there are a number of technical challenges. These include gross segregation of particles due to gravity or coalescence; segregation to interdendritic or intercellular regions which is affected by interfacial energies, particle size and volume fraction, and physical properties of the particle; and inadequate understanding of melt rheology [65]. The selection of specific particle(s), and their size and volume fraction are limited by the chosen process; an excellent understanding of the synthesis process is required. More practical issues relate to machining and joining/assembly.

Many of the fiber and matrix materials of interest for very high performance composites exhibit poor ductility and fracture toughness which, when combined with environmental resistance problems, leads to composite processing problems and reduced composite properties, especially in the composite's ability to handle thermal stresses [40]. The fact that these materials are so difficult to work implies, in addition, that fiber damage will occur during processing; this is frequently observed. For example, titanium aluminide composites exhibit poor formability characteristics due to the brittle nature of the matrix; thermal stresses are also a problem [37, 40]. These thermal stresses arise from the thermal expansion differences between the fiber and matrix as the composite cools down from the relatively high fabrication temperature required for titanium aluminide composites. In some cases, matrix microcracking and fiber debonding and breaking, each of which can reduce modulus, strength, and other properties, occurs [37, 79]. Thermal stress cracking is a function of misfit strain, matrix toughness, modulus, and reinforcement size, shape and volume fraction; it is especially important when the matrix material is brittle and under thermal cycling conditions. There is concern about effects of these thermal stresses: the matrix must be able to support such stresses without cracking. Mortensen *et al.* [54] point out that large thermal expansion mismatches between the reinforcements and matrix can result in high dislocation densities which, in turn, affect the heat treatment characteristics of the composite.

Toughness, important for a material to handle thermal stresses, is a function of the matrix and interface so processing is crucial: toughness values for MMCs are usually below those acceptable for critical structural components [55]. If the matrix is ductile, crack initiation occurs at the interface, usually at a brittle reaction layer; when the matrix is brittle, the critical flaw size is smaller than the fiber-to-fiber spacing so cracks typically initiate in the matrix. One would like the interface to be strong enough for load transfer until the matrix fractures, then weak enough to allow debonding. Toughening mechanisms are based on microcrack branching in the matrix and on interface debonding: fibers in cMMCs provide crack bridging behind the crack front by pull-out or by ductile extension. Interfaces can be tailored somewhat via the use of single- or multi-layer coatings to provide the characteristics noted above and to meet the required properties. But the practical questions (and fundamental understanding) regarding what kind of coatings, how many layers, how thick should each layer be, etc. are difficult to answer; it's typically done via "trial and error" [e.g., 78] though analytical methods/models have been developed [e.g., 75, 76, 79, 83, 86]. As one might expect there is a trade-off among properties: for example, a high interface strength is desirable for good creep properties. It appears that major improvements in matrix alloys and fibers are needed to address the inherently low ductility and fracture toughness as well as environmental resistance problems of these high performance composites.

Important intrinsic factors affecting toughness in the dMMCs include reinforcement type, size, shape/aspect ratio, volume fraction, and spatial distribution; the presence of reaction layers or precipitates at the interface boundary; and the presence of grain boundaries, precipitates, or precipitate-free zones in the matrix [84]. Extrinsic factors which affect toughness may include microstructural mechanisms such as crack bridging or deflection. Macrostructural approaches for improving fracture strength of these composites rely mostly on the introduction of internal interfaces or on the combination of two different materials with different toughnesses to improve damage tolerance: an example of this might be a laminated structure consisting of a layer of dMMC sandwiched between two layers of unreinforced metal. The desired component properties, component geometry, orientation, and interface strength are key features of these macrostructural approaches [84]. Toughness can be significantly enhanced by these macroscopic mechanisms.

Fatigue behavior in the dMMCs is influenced by particle size; the effect of distribution is less clear. When particle sizes are very fine the fatigue crack growth threshold is below that of an unreinforced alloy while for coarser SiC particles the threshold is equivalent to that of the monolithic alloy [85]. At higher ΔK, in Stage II, both fine- and coarse-particle composites exhibit increased fatigue crack growth resistance compared to the unreinforced alloy, attributed to increased crack tip shielding, which is followed by decreased crack growth resistance, attributed to particle cracking and decohesion. Whisker-reinforced composites appear to exhibit better fatigue properties: an increased number of cycles to crack growth initiation is typically observed relative to the particulate-reinforced or monolithic materials.

Methods by which the constituent materials are integrated are often inconsistent and processes by which they are fabricated frequently vary from batch-to-batch though progress and, correspondingly, improved properties have been noted for the dMMCs since they are much closer to being production level materials. Extrusion and forging of the dMMCs are generally considered difficult due to relatively low composite ductilities though within limits high rate forging is apparently feasible. However, the large amount of scrap generated in such processes is an issue with relatively expensive dMMCs [45]. Allison and Cole [45] are also concerned about the possibility of thermal aging at 300-450°C and stress relaxation that may occur in dMMCs during such secondary fabrication processes.

An important consideration for solid state processes used in the fabrication of cMMCs is the volume change that occurs during that consolidation: it affects external dimensions as well as local stresses on the fibers [55]. These local stresses can cause fiber interface damage, displacement (swimming), compression buckling, or tension failure. The particular manufacturing technique and the arrangement of fibers affect the direction and amount of metal flow during consolidation along with the magnitude of the volume change. For most hot pressing operations, displacement occurs in the ram direction but resultant stresses in other directions can result in the fiber problems noted above. PVD matrix-coated materials can be packed more closely which allows for higher volume fractions and lower reductions in thickness than the foil-fiber-foil process and, correspondingly, lower stresses reducing the likelihood of fiber damage, etc.

In terms of other processing defects, it is believed that plasma spray processes may damage fibers or the thin, protective coatings over them due to the high speed of the droplets and to thermal/mechanical shock impacts [55].

Incomplete removal of organic binders, as would be used in a number of the MMC manufacturing processes for preform stability prior to infiltration or consolidation, can lead to contamination and reduced mechanical properties [55].

Conversion and Commercialization Barriers

Two of the biggest challenges facing the advanced materials industry today are how to rapidly commercialize laboratory-developed technology and how to convert defense technologies into something of interest to civilian markets [87]. U.S. industry not been very successful in commercializing advanced materials, assuming "materials commercialization" is defined as "the cost-effective production and application of advanced materials to meet global market needs" [88]. In the past the Federal government assumed the responsibility (i.e., risk and cost) for commercializing materials via component development, feasibility demonstration, and engineering development programs. The government needs to ensure the purchase of advanced military and space systems made using such materials in the future so commercialization (emphasis on dual-use) will be important for industry survival.

A number of factors appear to increase the likelihood of successful commercialization [88-90]: an early market assessment for a strong, clear product concept; a balance of risk with potential payoffs; consideration of R&D costs and pilot manufacturing/product introduction costs (which represent the lion's share of total cost) with respect to total cost; enthusiastic, but not overly so, champions at the technical and executive levels; a small, motivated, cross-functional team with ownership of the technology and resources to do something about it; availability of a skilled, stable workforce; consideration of the real customer - the parts fabricator; good end user-supplier-fabricator communications on a detailed technical level; making the correct business integration decisions either upstream into raw materials or downstream into semi-finished, fabricated parts; consideration of other applications since multiple niche markets are more common for newer materials; emphasis on continuous improvement; and use of off-the-shelf components when feasible rather than re-inventing the wheel. And it always helps to have a public eager to buy the product. The problem is somewhat exacerbated by the rapid rate of technological change in materials, in particular the decreasing technological half-life [89]: half-lives of 30 to 40 years, common for older materials such as glasses, clay products, whitewares, and ferrous metals, have been reduced to 5 to 10 years for new materials like composites and electronic materials.

Effects of the defense drawdown on the whole composites industry have generally been negative. Some composite suppliers/producers are leaving the business or consolidating. Other observations include declining sales, declining employment, low utilization rates in terms of operating capacity, an apparent technology outflow from the U.S., and unavailability of skilled labor [91]. Material suppliers appear to be the most affected but downstream fabricators and users are also affected. Industry R&D figures [91] indicate a growing dependency on Federal financial support, mostly from DoD, and suggest that U.S industry is less financially capable of converting to commercial applications. And this is particularly true for MMCs, the bulk of which have been produced for defense programs.

That said, what are the barriers that prevent commercialization of MMCs, or, for that matter, any advanced material? It is obvious to anyone studying the MMC industry that it is not mature [e.g., 19]. Barriers to its success can be grouped into one of three categories: economic, regulatory/legal, and technical.

Major economic barriers include the "high" cost of producing MMC materials and components, high being relative to particular applications, and small to non-existent markets [31, 32, 48, 88, 92]. Some telling comments from an ASME-sponsored (American Society of Mechanical Engineers) workshop on Research Guidelines for Aluminum Product Applications in Transportation and Industry are appropriate [93]. Dr. Bill Hoover, in describing Duralcan's business experience with SiC_d/Al composites, stated that "the longer I'm in the business the more I realize that business issues are more important than technical issues." Another significant remark was "if you make material good enough people will buy it ... wrong. They will only buy it if it doesn't cost too much." At the then $2 per pound their SiC_d/Al was still too expensive for many automotive applications because the finished component costs $6 or $8 per pound. At this same meeting, Dr. Ralph Sawtell described Alcoa's efforts to commercialize SiC_p/Al composites: Alcoa fabricated 100 connecting rods for Ford. While the connecting rods performed quite well they were too expensive and were not utilized for production. Cost is a particular concern for DoD: the dMMCs are relatively low cost (a few dollars per pound) but are often unable to meet performance requirements; the cMMCs exhibit the highest performance but are also quite expensive (thousands of dollars per pound). The current commercial market for cMMCs is essentially non-existent, a circumstance which implies small fabricated quantities and, usually, inconsistent quality. The high final component cost which comes about, in part, from relatively expensive raw materials for dMMCs is an important issue for the automotive industry as well [45, 57]. The material suppliers say, "If you will use it, it will get better and cheaper"; but the end user says, "When it gets better and cheaper I will use it." Unfortunately, for the cMMCs, replacement of existing components is probably not an option: these high performance materials will more than likely be used in new applications. The high cost of producing these materials and the resultant high prices at which they are sold as well as the fact that there are few substitutes with comparable performance characteristics mean a user cannot easily respond to changes in price: demand is inelastic [92]. A low elasticity implies that the reduction in price needed to increase use of the material is large, which, in turn, suggests that improved performance capabilities are insufficient to bring about a market increase. Therefore, to reduce the cost (and to achieve dual-use goal for DoD), it appears that lower performance materials with broader market appeal will be needed. Other economic barriers [31, 45, 88] include the high costs associated with and long time required for materials R&D and scale-up to production weighed against the risk of failure; the high cost of capital facilities and the lack of incentives to invest in them; short term management goals (profit considerations); government procurement and funding policies; and government funding uncertainties created by an annual budget cycle [e.g., 88, 94]. Bryant notes the difficulty associated with convincing a customer that down-stream savings based on parts consolidation or longer life is worth the additional cost of MMCs [34]. Arnold [51] specifically identifies the issue of capital investment in iron and steel structure fabrication technologies - especially sheet, bar, and bulk processes - for the automotive industry as well as an emphasis on design capabilities in those areas. He further states that the experience base on advanced composites from the aerospace industry is of limited utility due to very different cost drivers and processes [51, 57]. Any new materials technologies to be used, particularly in high volume applications, will probably have to be low risk and compatible with the existing basic manufacturing and assembly infrastructure. Another issue faced by the U.S. MMC industry is that producers have been/are being bought by foreign competitors.

Among the most significant regulatory and legal barriers are intellectual property rights, especially problems related to legitimate use of patents and exclusivity under government contracts, difficulties associated with enforcing process-intensive patents, and protection of proprietary information [e.g., 31, 88, 95]. Other barriers include anti-trust concerns, export restrictions, and environmental, health, and safety regulations. Environmental regulations are likely to become increasingly important. For instance, CAFE and emission standards, particularly important to the transportation industry, are expected to become more stringent in the future.

One of the major barriers preventing MMCs from being more widely used is related to the technical complexity of these materials. This technical complexity includes such items as MMC material and product inconsistencies; insufficient materials, design (especially for fatigue, creep, wear, and corrosion properties), and processing databases; the absence of adequate standards for MMCs, processing methods, and inspection and testing procedures (including qualification); a lack of intelligent processing (IPM) approaches; the general absence of an integrated product and process development approach (basically a systems approach) including concurrent engineering methodologies, multi-disciplinary design optimization, product/process life-cycle cost modeling, automated fabrication and assembly, and rapid prototyping; a lack of environmentally clean materials, processes, and manufacturing approaches in the form of recyclable materials, recycling processes, and low energy or alternative processes; and inexperienced labor and inadequate education related to manufacturing [e.g., 19, 31, 34, 45, 53, 88, 94]. The fact that new materials, with typically incremental property improvements, are continually being developed (or old ones are being tweaked) exacerbates the problem of material and product inconsistencies and makes commercialization inherently more difficult as well: it is difficult to obtain the same material from year to year, a situation which complicates designer/user acceptance and limits usefulness of the available data. Other identified barriers include a scarcity of joining and assembly techniques, a limited understanding of reinforcement/matrix interfaces, insufficient low cost/high volume fabrication processes, especially near net-shape (NNS) processes, and few reliable repair processes [35, 45]. Shortages of fast, inexpensive machining methods and of information on machine tool life and wear are particular difficulties for companies producing large volumes of components [53, 96].[13] Specific technical gaps have

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[13] The primary inhibitor is the high tool cost resulting from frequent replacement due to wear. This is less of a problem using polycrystalline diamond (PCD) tools which are 5-20X more expensive than carbide

been identified for both cMMCs and dMMCs [31, 53, 57, 94]. These issues can generally be related to reinforcement - forms and producibility, cost, coatings, and coating methods; matrix material development either in terms of alloy development or product form; particular reinforcement/matrix integration methods; reinforcement/matrix interfaces and reactivity; processing-property-microstructure relationships and trade-offs; joining and other secondary processes; and size and equipment limitations. Fenter [94] mentions a lack of design methods and fabrication techniques for complex, non-isotropic structures.

What Next - Summary and Conclusions?

Issues associated with MMCs and steps thought necessary for future technical and commercialization efforts have been identified by many. For instance, the AMMT Working Group has identified five general needs and the requirements (R&D, etc. efforts) to achieve them [20]: a healthy industrial base; lower cost everything; improved reliability of materials, processes, and structures; environmentally compatible materials and processes including joining/assembly, repair, and recycling; and higher performance systems. I have chosen to group the categories as follows: materials, processing approaches, characterization and testing methods, analytical methods and tools, and engineering aspects. The attribute of "low cost" can be attached to any one of them.

For materials there is interest in low cost reinforcements, especially fibers, and matrix materials [20, 97]; synthesis of better (higher strength) fibers and other improved reinforcements [55, 93, 94]; better matrix materials and fiber coatings to improve transverse creep and tensile properties without sacrificing fracture toughness for high performance composites [41, 42]; new matrix alloys specifically designed for composites along with a fundamental understanding of matrix metallurgy and micromechanics [54, 55, 97]; better understanding of fiber/matrix interface interactions [55]; standardized materials [20, 93]; durable, corrosion-resistant materials [20]; recyclable materials [20]; environmentally clean materials [20]; lightweight materials [20]; high temperature materials, especially for the matrix [20, 94]. Areas that may be worth additional investigation to improve the fracture behavior of the dMMCS are studies on the effects particle shape, precipitate characteristics, solute distribution, and grain/subgrain structure [84]. Some in industry prefer to see better use of existing materials rather than development of new ones ; there is a strong sense that no more high cost, exotic materials should be developed [93].

Achieving the processing needs identified below will probably be a key factor contributing to the ability of the MMC industry to successfully commercialize its materials. The AMMT [20], for example, mentions critical requirements as intelligent NNS processing, automated fabrication and assembly, standardized processes, rapid prototyping capabilities, environmentally clean material manufacturing and post-fabrication processes, low energy processes and manufacturing approaches, and commercially feasible processes. Cost effectiveness, rapid and reliable processing, including recycling, are frequently mentioned in the same breath [35, 54, 93, 94, 97]. Low pressure processes need to be made more economical via improved understanding of wetting characteristics and infiltration physics and intelligent design of gating, chilling, venting, and liquid metal delivery [54, 55, 94]. Higher production volumes are also desired but product standardization ala a product line is probably necessary in order to

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tools but last 2X to 6X longer [45]. In a study comparing machining of cast iron brake rotors with carbide and ceramic-tipped tools and SiC/Al rotors with PCD tools, the machining cost per part was less for the composite - $1.57 vs. $1.72; the machining rate was faster as well - 3131 rotors per day, 65% above rate for cast iron rotors [96]. In another study results of a total cost model showed that machining SiC/Al was half the cost of machining Ti and a bit more than 2X cost of machining aluminum.

achieve that [54, 57]. Further development of NNS processes and the development of semi-finished shapes such as rods, tubes, and sheet should be pursued [93, 97]. A need for more efficient methods for making fiber preforms for the infiltration processes has been identified [54]. Included with that might be approaches to integrate fiber treatment, interface tailoring, and preform geometry selection steps [55]. Process details of interest include better understanding of temperature, pressure, atmosphere control of pressure-infiltration processes [54]; better understanding/further development of processes such as HIPing, extrusion, liquid-metal infiltration, diffusion bonding, shear spinning, and high speed machining/forming/joining, etc. [94]; development of artificial intelligence (AI) process controls [94]; and a better understanding of microstructure-property relationships with respect to flow and fracture in casting methods [55]. Development of appropriate databases for all of the processes will be helpful to both fabricators and design engineers.

Most references cited in this paper agreed on the need for standardized characterization and testing methods and on the need for on-line NDI/NDE techniques, for process control and improved material reliability [e.g., 20, 93, 94, 97]. Specific composite analysis techniques for hydrogen content, volume fraction of reinforcement, and chemical analysis of matrix alloys were also mentioned [57]. Others have identified the need to limit materials proliferation and concentrate on thoroughly characterizing a few composites [54]. NDE methods to detect initial and service-induced damage are desirable, particularly for the high performance materials used in critical structural applications [41, 42]. Some characterization and testing methods are meant specifically for the high performance composites and include accelerated test methods, high temperature test methods, and appropriate validation testing for components [20]. Some in industry feel materials characterization to provide relevant data for commercial rather than aerospace applications should be accomplished by serial production runs and realistic testing [93].

Most of the identified needs for analytical tools and methods involved cost-benefit processing/property models, product/process life-cycle cost models, and life prediction models [20, 35, 41, 42].

Engineering aspects focused partly on design approaches for composites and included the following: multi-disciplinary design optimization and concurrent engineering [20, 35, 94]; the development of composite system (fiber, matrix, and coating) design methodologies especially for low ductility materials [41, 42, 54]; development of new structural concepts [20]; and design/analysis tools such as design handbooks and durability analyses [94]. Other identified needs were more practical: development of joining and assembly methods and repair technologies, especially for cMMCs [20, 35, 93, 94, 97]. Hoover identified the fact that quality standards used for a new material that is being substituted in an old application are related to existing ("old") product specifications and may not, in fact, be appropriate [57] so an understanding of the component properties and its performance requirements is important [55, 93]. Demonstration projects such as space structures, hypervelocity aircraft structures, and guidance control mounts were among those suggested [93, 94].

How can the government and industry work to overcome economic, regulatory and technical commercialization barriers? A review of the literature indicates similar thinking by a number of different groups on the role of government [e.g., 31, 45, 87, 88, 91, 92, 95, 98]. It seems clear that long range national objectives should be established by the Federal government with significant input from industry, mostly via trade associations and professional societies: according to some the vision must come from industry [95]. A number of sources suggest better coordinated efforts and communication between government agencies, and between government and industry groups. In fact, the NMAB study [88] suggested that the Federal government act as a clearinghouse for broad dissemination of materials R&D information, a national database as it were. More Federally-supported programs to address technical issues and manufacturing science and technology, especially for development of low-cost processes, at the material supplier level are a common theme. Many in industry believe that the government should move away from supporting the creation of new materials to practical programs that encourage implementation of existing materials and technologies [95]. Other suggestions include formation of a central technology development office within the government [91] and expansion of the technology extension service concept [95]. It is thought that needs to reduce the cost of using and producing MMCs and to increase their commercial viability can be addressed by Federally-supported, dual-use demonstration and field testing programs, possibly via military retrofits, as well as by changes in economic policies ala R&D tax credits, procurement practices, and export control restrictions. Other roles commonly identified include the development of materials standards, standardization of design-related materials property databases, and provisions for education and training assistance.

The role of industry is somewhat less clear though it appears that most are looking for as much financial support from the government as they can get: the MMC industry would like to see a nominal real growth of 10 to 20% in R&D funding by 1999 [94]. Trade associations believe one of their important roles is preparing detailed technical roadmaps for the government [94, 95]. Some suggest a need to focus more strongly on customer needs and on communication among the relevant groups - suppliers, fabricators, and end-users [e.g., 87, 88]. Open communication between suppliers and users can help address the perceived lack of awareness of the importance of materials on the users part [95]. Information on benefits of MMCs and design and fabricaton methods also needs to reach small companies. But since there is not a culture of information sharing, technology diffusion may be difficult. Pilot programs and industrial consortia focused on cooperative, cost-shared efforts, particularly addressing process efficiency and product quality issues, may improve the chances for successful commercialization [e.g., 45, 87, 94]. Some companies, like Duralcan, have chosen to bear the entire cost of addressing technical issues related to processing and fabrication as well as commercialization and all it entails [53, 57]. In terms of education, industry involvement in local schools can help increase awareness at the K-12 level. Education and training efforts can be aided by university involvement. Such activities could include new undergraduate programs, e.g., the "practice school" concept, focused on design, processing and manufacturing with advanced materials; continuing education programs for degreed engineers; and practice-oriented training programs at the skilled labor level [88].

With all of the aforementioned difficulties associated with commercializing MMCs is there any possibility of success? Some are skeptical of defense to commercial conversion efforts due, in part, to the culture shock experienced by defense contractors in terms of commercial world values and economic factors. In addition, defense contractors, including material suppliers, have problems meeting performance targets, deadlines, and cost demands. DoD is essentially the only agency that buys the products it develops. MMCs are an example of something developed by DoD that did not consider commercial markets and that has, therefore, taken a long time to achieve any progress, much less application. So the importance of niche markets appears to be critical to any acceptance of MMCs, both discontinuous and continuous, at least for the present. Brown *et al.* [31] suggest that there are two primary market segments: one is for MMC materials with dual use applications ala dMMCs for automotive applications and graphite fiber-reinforced MMCs for thermal management applications; the other is for high temperature MMCs (especially TMCs and IMCs) with generally limited commercial applications, except perhaps in some aerospace products. It is their belief that the second area will require extensive government support to bring to fruition though there is potential for useful government programs to address both market areas: e.g., issues associated with reinforcement/matrix interfaces, secondary fabrication processes, and market awareness. Bryant projects that MMCs will not penetrate the market very much until after 2010 [34]. McDonough [19] concludes that materials which provide adequate performance at the best price will prevail in the commercial arena. Projections for MMC shipments in 2002 suggest significant growth in the U.S. in the automotive sector relative to 1992 estimated shipments; only mild increases are projected for aerospace, recreation, and industrial/other sectors [19]. Primary sources of foreign competition to the U.S. MMC industry are Japan and the United Kingdom [11, 12, 94]. The Japanese, in particular, have directed their efforts toward commercial applications with a strong emphasis on processing and process economics, particularly for whisker-, particulate- or fiber-reinforced aluminum composites [94, 99, 100]. Their more recent efforts are focused on high performance materials (C-C and IMCs) for severe environments, similar to NASP.

It is obvious that there are many significant issues to be addressed before these materials will be widely used. It appears that, in order to be successful, MMC material suppliers will be required to have a thorough understanding of customer needs and materials, process, and product design. They must also have the process control necessary to make consistent, high quality products that meet increasingly stringent performance and environmental specifications for aerospace as well as other applications. A comment from *Washington Technology* nicely summarizes the key generic factors that need to be addressed for successful commercial utilization of advanced technologies [101]. These critical factors include defining the customer; finding a real problem that a customer has and wants to solve; and determining how the technology in question creates the solution. These factors are particularly relevant to the application of advanced composites. The ultimate goal is to meet the customer's needs: "what may well be an advance in technology doesn't always translate to measurable or discernible benefits to a citizen consumer or business person" [101]. While the properties of the MMCs make them quite attractive for a number of diverse applications, their ability to overcome the identified barriers - economic, regulatory, and technical - remains unclear.[14]

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[14] I think it is interesting to note that many of today's advanced materials, including the MMCs, are unlike the advanced materials of the somewhat distant past, e.g., fiberglass composites. Fiberglass composites became popular for craftsmen and relatively unskilled "back yard" builders because they were easy to use, minimum levels of skill and capital investment were required, and, eventually, fewer hours were required to produce quality components (e.g., boat hulls) in production runs of more than one or two. Today's advanced materials may not have as many of these advantages. The economic reality may be that current advanced materials, like the MMCs, will not be widely used.

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