SPECIAL REPORT

Advanced materials and impact on mineral producing countries

by Carmine Nappi

In order to better understand the impact of advanced materials on producers of traditional metals, this paper provides an analysis of their different end-use markets. Unless the prices of traditional metals increase substantially or if new regulations on the environment greatly stimulate the use of advanced materials, their direct impact during the next decade will be less dramatic than previously expected. Despite this, mineral producing countries should continue their monitoring of advanced materials. They represent the media that diffuse new technologies through industrial economies. Also they may provide opportunities for improving mining and mineral processing technology.

This paper was presented at the First International Symposium on Mining and Development, Campinas, Brazil, July 1995. See also RMR Vol 11 No 2.

Carmine Nappi is professor of the Institute of Applied Economics, École des Hautes Études Commerciales, 5255 avenue Decelles, Montréal, Québec, Canada H3T 1V6.

Even if advanced materials are usually defined as those materials, developed over the last 30 years or so, that exhibit greater strength, higher strength/density ratios, greater hardness, and/or one or more superior thermal, electrical, optical or chemical properties when compared with traditional materials [1], such a definition does not highlight other major differences. The production of the former does not usually benefit from economies of scale, it requires a different mix of inputs (human capital, R&D, scientific knowledge rather than physical capital, mineral or energy resources) while the properties of advanced materials can be customized. The suggested definition does not take into account the fact that advanced materials are more difficult to recycle, that they may have significantly different environmental implications from those of traditional materials, or that they have an "enabling" aspect in the sense that they exhibit greater potential for rapid technological advance and market penetration.[2]

But agreeing on a common definition does not represent the only bone of contention among economic analysts of the advanced materials market. When asked to evaluate the potential market value of advanced materials by the year 2000-2005, to identify the main end-use markets where these new materials may be used, or to speculate on the economic impact of their adoption on mineral producing countries such as Brazil, their answers vary to a great extent. This paper revisits these issues.

Forecasted and observed consumption

The list of materials displaying the main key characteristics (high value-added niche products, intensive in human capital and scientific knowledge, exhibiting exceptional properties and using sophisticated fabrication processes adapted for the production of customized products) of the advanced materials may be quite long, including specialty or composite glasses, metallic powders, carbon-carbon composites, room temperature superconductors or electrically conductive polymers. This paper only considers three classes of advanced materials:

- monolithic ceramics and ceramic matrix composites (CMCs);
- polymers and polymer matrix composites (PMCs);
- advanced metals (advanced aluminum alloys, superalloys, titanium alloys, intermetallic alloys) and metal matrix composites (MMCs).

The consumption of these advanced materials increased quite substantially during the '80s, the annual growth rate of their shipments averaging 15 per cent. Such a performance may be explained by factors such as the longest economic expansion of the post-war period and the increased military budgets following the Soviet invasion of Afghanistan (the production of stealth fighters or of intercontinental ballistic missiles required new materials with specific characteristics in terms of weight, hardness, optical or chemical properties). Other factors include the space race (the development of the space shuttle or of the space station requires very performing materials in order to resist a very harsh environment), the increased budgets for governmental and university laboratories working on energy problems or in materials sciences, and finally the breakthroughs in computer sciences which have allowed a better understanding of the organic and inorganic matter.

Analysts of this industry assumed during the mid-80s that these factors would continue to exert their positive influence on the shipments of advanced materials for many years to come. The ceramic fever or the composites craze of that period made them forecast an American consumption of 750 MUSD for the MMCs or of 550 MUSD for the aluminum-lithium alloys for the year 1995. In the case of advanced ceramics, the forecasted shipments for the year 1995 were somewhere between 7 700 and 14 600 MUSD depending on the definition used, while a forecast of 1 500 MUSD was suggested for the American consumption of PMCs (3 100 MUSD worldwide).[3] As can be seen from Table 1 such forecasts never materialized.

The U.S. production of MMCs for the year 1993 barely exceeds 30 MUSD (half of the value of world production of MMCs) or 4 per cent of the level forecasted for the year 1995. Not only the U.S. and world production of MMCs are marginal but also they have remained quite stable since the beginning of the '90s. In the case of the aluminum-lithium alloys, their production never took off. The forecasts were not more precise in the case of the advanced ceramics. The 1993 value of the U.S. production of these new materials represents 50 per cent of the more pessimistic forecast suggested for the year 1995. The situation has been quite different in the case of the PMCs. During the mid-80s, their shipments were forecasted at 1 500 MUSD for the year 1995. This estimate may materialize since the value of U.S. production of PMCs has been declining since the beginning of the '90s when it reached the 2 400 MUSD level. It leveled off at 1 900 MUSD in 1993. Therefore, even if the forecast seemed initially to underestimate the market value of the American production of PMCs, it may become accurate if the decline continues two more years. How do we explain such a disappointing performance? Which factors have hindered the growth rate in the production of advanced materials?

Even if many reasons may be invoked to explain the atrophy in the sales of advanced materials, the following factors need to be underlined.[4] First, a flow of new investments was spurred on by the optimistic forecasts of the mid-80s, some companies paying too much for acquisitions, in return for a rapid entry in the field. Others ill-planned their capacity expansions. The economic recession of the last three years has forced them to reduce their profit margin and thus to shrink their level of production. Second, the end (at least for now) of the cold war provoked a worldwide and important atrophy in national defence budgets, thus reducing the demand for advanced materials originating from this significant end-use market. Many firms tried to substitute the military by the commercial market. They realized that this task is not an easy one. In some industries (like the automobile sector) the adoption process may be a lengthy one (6 to 10 years). Also, commercial firms usually face a more price-elastic demand curve than military firms, the price of products becoming a selling tool at least as important as their performance. Such a perspective has reduced the present value of the income streams expected in the future, thus persuading some firms to scale down their activities and others to pull out altogether (this has been the case for Rhone-

Table 1. American and world production of advanced materials: 1990 – 1993

	Metal matrix composites		Composites ceramics[1]		Advanced ceramics[2]		Polymer matrix composites	
	Volume kt	Value MUSD	Volume kt	Value MUSD	Volume kt	Value MUSD	Volume kt	Value MUSD
American production								
1990	0.2	36	–	3 800	–	–	9.0	2 400
1991	0.2	33	–	3 900	–	–	7.8	2 400
1992	0.2	31	–	–	124.5	3 173	7.4	2 200
1993	0,2	31	–	4 000	126.4	3 289	6.7	1 900
World production								
1990	0.5	60	–	13 600	–	–	15.0	4 000
1991	0.4	54	–	15 300	–	–	14.1	4 500
1992	0.6	56	–	14 800[3]	583	13 373	13.7	4 300
1993	0.7	63	–	18 300[3]	594	13 911	12.6	3 900

Notes: 1. Derived from Ceramic Industry. 2. Derived from Kline & Co. Inc. 3. Includes $ 1.18 billion for optical fibers not in Kline data.
Sources: McDonough, W.J., Advanced Materials 1992, U.S. Department of the Interior, Bureau of Mines, Washington, February 1994, p. 43. U.S. Bureau of Mines, Mineral Commodity Summaries 1994, U.S. Department of the Interior, Washington, 1994.

Poulenc's ceramics and composites division, British Petroleum's particles division, BASF Structural Materials or Alcoa Composites).[5]

Third, engineers and technicians have for years worked with traditional materials such as aluminum, copper, steel or zinc. They have accumulated abundant knowledge about their behaviour in various physical environments. This is not the case with the advanced materials for which the databases are far less complete (for example, the anisotropic character of advanced composites presents additional difficulties in generating acceptable databases). Given these facts, their reluctance to adopt new materials and therefore their inertia or their play-it-safe conservatism are understandable.

Even if the economic recession, the reduction in defence budgets and the "cautious conservatism" of engineers and technicians explain a large part of the atrophy in the consumption of advanced materials, we should not forget even more important handicaps such as the remaining unsolved technical problems hampering the production of some advanced materials and of course their relative high prices (especially in the case of composites). For example, ceramics are still too brittle and unable to withstand temperature cycling. Their resistance to oxidation is too low to be used in engines. In the case of MMCs, their high strength and stiffness are achieved at the expense of two properties that are considered among the virtues of metals — ductility and toughness. The production of PMCs remains labor-intensive and they do not lend themselves to automated production. Also, their compressibility can be too high and their transverse strength and stiffness too low to allow them to be substituted for metals in all structural applications. Finally, composites using continuous fibers may be difficult to repair and impossible to recycle.[6]

The importance of these factors has not been fully appreciated in the past. Those in charge of medium- and long-run forecasts for the production or use of advanced materials have preferred the more comforting hypothesis that technical solutions would in time be found and that these materials would fully realize their economic potential. What about the relatively high prices of advanced materials? As mentioned by the European Composites Director of Du Pont International: "These materials are still mainly associated with high-tech aerospace applications, where material cost is less of a consideration. Nevertheless, progress towards cost-effective manufacturing technologies has been slow; hence the lack of greater penetration into the automotive and other cost-sensitive markets".[7] When talking of relative costs or prices, we must pay attention and realize that the only relevant cost consideration in materials substitution is the so-called "total package cost". This cost includes not only the price of the material itself, but also all other costs involved in using the material to manufacture a product. Despite their higher costs, the new materials may still be preferred because they offer the opportunity to reduce manufacturing costs sufficiently to offset their higher prices. If advanced materials are not more often used, it may be because materials producers do not work closely enough with parts designers and other manufacturing system specialists to develop a product that is competitive notwithstanding their higher prices.

Despite all these technical, economical and marketing problems, the advanced materials industry remains a very significant industry with 1993 sales exceeding the 20 000 MUSD level. Its shipments may have increased at a slower pace than expected, but they still exceed those of many metal industries. Also, non metallic components make up almost 10 per cent of an average car's weight.

They are increasingly used in sports and recreational equipment, and in medical/orthopaedic equipment. Composites market shares of next-generation helicopters, combat and commercial aircrafts or military engines will be much higher than actual percentages. In order to better understand the possible impact of advanced materials on producers of traditional materials, the next section provides a more detailed analysis of their different end-use markets. Advanced ceramics which represent about 70 per cent of the total shipments of the advanced materials industry will be studied first.

MAIN END-USE MARKETS FOR ADVANCED MATERIALS

Advanced ceramics

Even if no standard definition exists, there is a fairly uniform consistency in the segmentation of the advanced ceramics industry into electronics and engineering segments. The former represents a mature business (its first products gained commercial acceptance in the 1950s) and it typically includes substrates and packages for semiconductors, capacitors, piezoelectrics and resistors. According to Table 2, electronic ceramics represented in 1993 the largest segment (73 per cent) of the U.S. advanced ceramics industry and is projected to grow at 7-11 per cent through 2000. The latter market (the more threatening from the traditional metals point of view) is more fragmented and less mature. It includes wear parts, pump and valve components, engine components, cutting tools, biomedical ceramics, heat exchangers, etc. Even if the U.S. sales of structural ceramics reached almost 900 MUSD in 1993 (or 27 per cent of the U.S. market), shipments of monolithic structural ceramics represented less than 25 per cent of that value, the difference being made of ceramic coatings and of CMCs.

Given the physical advantages of structural or engineering ceramics (high strength at elevated temperatures, corrosion and wear resistance), how do we explain their small market share? Mainly by the brittle nature of ceramics which is caused by the propagation of microfrac-

Table 2. Estimated 1992 – 1993 U.S. sales for advanced ceramics, by technology

	Electronic ceramics		Ceramic coating		Engineering ceramics		Total advanced ceramics	
	Quantity kt	Value MUSD	Quantity kt	Value MUSD	Quantity kt	Value MUSD	Quantity kt	Value 000 MUSD
1992	67.0	2 324	49.0	654	8.3	195	124.3	3 173
1993	68.8	2 416	49.1	669	8.5	204	126.4	3 289

Note: According to Deckman (1993), the corresponding figures for the world market are the following for the year 1992: electronic ceramics (4 – 9 000 MUSD), ceramic coating (800 – 1 700 MUSD), engineering ceramics (1 300 – 2 300 MUSD, this figure including the ceramic matrix composites, 100 – 300 MUSD). The total market value oscillates between 6 100 – 13 000 MUSD depending on the definition used.
Source: Table derived from sources cited in Table 1.

tures, which may result in a sudden catastrophic failure. According to Deckman, ceramic coatings were initially developed as an interim solution, while technical obstacles with monolithic ceramics were being addressed.[8] Table 2 shows that this segment has increased quite fast to become the second largest market of advanced ceramics after the electronic sector. CMCs were also developed to overcome to a certain degree the brittleness problem by the introduction of a reinforcing agent into a ceramic matrix. Despite their increased fracture toughness and their greater hardness, these composites are still in their infancy and are used mainly as cutting tool inserts and in the aerospace sector, their most well-known application being as tiles in the space shuttle.

To sum up, even if advanced ceramics represent about 70 per cent of the shipments of advanced materials, almost three-quarters of these sales are made of electronic ceramics mainly used as substrates and packages for semiconductors, an end-use market where these ceramics cannot be considered as direct substitutes of the traditional metals. The potential capacity of advanced ceramics to displace metals is much higher for engineering ceramics where they may compete with the traditional materials in the motor vehicle manufacturing sector (hot parts of car and truck engines, turbocharger rotors, piston rings or cylinder liners) and in the aerospace industry. This potential threat for the traditional metals (in particular steel and aluminum) has not yet materialized because of the technical problems mentioned above. The outlook seems brighter for ceramic coatings which are used as an alternative to monolithic ceramics to protect or lubricate a material against deterioration. The demand for these coatings has increased because of their lower unit costs, their smaller quantity of the expensive ceramic material needed and the possibility to recoat a worn part instead of discarding the entire component. To the extent that in many applications ceramic coatings may be considered much more as complements rather that substitutes of metals, they should not keep the metal producers awake. The situation is quite different in the case of PMCs.

Polymer matrix composites

PMCs are by far the most used composites. This is not surprising when one considers their low density, their very high specific strength or stiffness, or their capability of being formed into complex shapes, thus reducing the number of component parts of certain end products. Despite such advantages, the volume and value of their production have been decreasing since the beginning of the '90s. Even if the factors mentioned above explain a good part of this decline, other variables need to be mentioned such as their labor-intensiveness, their too high compressibility, and their too low transverse strength to be considered as substitutes for metals in many structural applications. The difficulty of repairing and recycling the continuous fiber composites should also be mentioned. Table 3 confirms that these materials are still mainly used in the United States (55 per cent of world production). It also presents their main end-use markets: the aircraft/missiles/aerospace sector (40-50 per cent of the U.S. and worldwide shipments), the recreation (20 per cent) and armor (15 per cent) industries and, finally, an emerging end-use sector, the automotive market (15 per cent of the U.S. shipments in 1993 and a forecast of almost 20 per cent for the year 2003).

PMCs have several advantages over the aluminum alloys they replace in the airframe and other structural applications. The most significant of these is the lighter weight of composites since aluminum parts generally weigh about 1,3 times as much as the composites that substitute for them. This characteristic enables the aircraft to have a longer range and/or bigger payload, operation from shorter runways, increased maneuverability and/or speed, and lower fuel consumption. For military aircraft, these attributes are considered crucial. For commercial aircraft, the main advantage is the increased fuel efficiency. Given that the price of fuel represents almost 60 per cent of the operating cost of a commercial aircraft, the savings generated by the use of PMC parts may offset their higher prices compared with aluminum. Other advantages include savings in fabrication and assembly costs since fewer parts and less machining are required. These advantages explain why the use of composites in McDonnell Douglas aircraft's military planes has increased from about 1 per cent of the structural weight of the F-14 to 10 per cent for the F-18. This share has reached 26 per cent on the AV-8B Harrier currently in production. Table 3 suggests that that PMC shipments will increase at an annual rate of 7 per cent during the 1993-2003 period. This forecast seems based on the assumption that composites will make up 80 per cent by weight of the structure of a next generation helicopter, 35-50 per cent of a combat aircraft, and 8-12 per cent of a Boeing 777 or Airbus A340. But despite this breakthrough, one should note that PMC world shipments to the aircraft market have declined by 25 per cent between 1993 and 1992. The monitoring of this end-use market remains thus extremely important for the PMCs producers.

The U.S. recreation industry consumed in 1993 more than 1.3 thousand tons of PMCs. Aramid fibers (Kevlar) are used in the production of sailing or motor boats in order to get a light but still very rigid structure. Also, the desire for better performance regardless of cost has created a market for fiberglass and carbon (sometimes graphite or even boron) reinforced PMCs in tennis rackets, golf club shafts, skis, sleds, toboggans, fishing poles, and bicycles. Their worldwide shipments are expected to increase until 2003 at an annual growth rate of more than 7 per cent. Such a performance may be possible if a decline in their prices permits a greater penetration of the larger volume markets actually dominated by the more traditional materials. On the other hand, demand facing the producers is more price-elastic in large volume markets, which implies lower profit margins.

What about the actual and future use of PMC in the automotive industry? Given their high price, these advanced materials were almost not used in 1993 but things may change in the near future as vehicle performance and environmental quality become the two driving forces behind the auto industry's push into new materials. Their use in vehicles is attractive because it eliminates corrosion from salt, their substitution for steel allows very substantial savings in fuel costs, while parts having complex contours and intricate internal supporting structures are more easily formed from polymers than from metals.[9] Also, the costs of molds and of other tooling for fabrication of polymers and composites is much lower than the cost of tooling for steel. Therefore, if the price is right, PMCs may be used in the near future in the production of package shelves, roof liners, battery trays, bumper beams, valve covers, engine intake manifolds, fuel tanks or engine shields. On the other hand, the outcome of materials competition for the production of exterior body-panels (potentially the biggest prize in the lightweighting bonanza) is far from being decided. The movement of polymer composites into body panels appears to be retreating since the thermal expansion problems (the materials expand when they move through paint ovens) have not satisfactorily been over-

Table 3. Estimated 1993 and projected 2003 worldwide advanced polymer composites shipments, by end use

	Worldwide		United States		Rest of World		Average annual growth rate per cent		
	1993 kt	2003 kt	1993 kt	2003 kt	1993 kt	2003 kt	World	United states	Rest of world
Aircraft	3.2	6.7	1.9	3.6	1.3	3.1	9.9	8.1	12.6
Missiles/Space	2.4	2.7	1.5	1.8	0.9	0.9	1.1	1.8	0.0
Recreation	2.0	3.6	1.3	2.2	0.7	1.4	7.3	6.3	9.0
Armor	2.0	3.1	1.1	1.8	0.9	1.3	5.0	5.8	4.0
Automotive	0.4	2.7	–	2.7	0.4	–	52.3	–	–
Industrial/Other	2.9	4.0	1.1	2.7	1.8	1.3	3.4	13.2	–
TOTAL	12.9	22.8	6.9	14.8	6.0	8.0	7.0	10.4	3.0

Source: Table derived from U.S.Bureau of Mines, Annual Report on Advanced Materials 1993 Data, Washington, 1994 (preliminary report).

comed. Also, these materials require electrostatic treatment before painting and are difficult to match with metal parts in fit and finish. For all these reasons, Table 3 suggests that the shipments of PMCs to the automotive sector will represent in the year 2003 less than 12 per cent of the expected worldwide total sales.

Advanced metals and metal matrix composites

Given the numerous breakthroughs of advanced ceramics and of PMCs in their main end-use markets, metal producers have not remained still. Thanks to progress in the science of metallurgy and its application to production processes, metal producers have developed not only microstructural variants of the metals produced by the conventional methods but also new metals and alloys that can only be produced by these new methods. These advanced metals possess to a higher degree than traditional metals such virtues as strength at elevated temperatures, lightness, microstructural stability, and resistance to corrosion, creep and to fatigue failure.[10] These engineering or high-performance aluminum, titanium, and intermetallic alloys have been developed mainly for the aerospace industry which remains their principal market. The shipments of these advanced metals have of course suffered from the atrophy in national defence budgets and the attempt by their producers to substitute the military by the commercial market has been all but an easy task.

The situation has been somewhat different in the case of the MMCs. Given their interesting properties (higher specific strength and stiffness at elevated temperatures when compared to the unreinforced metals; better malleability, lower cost, and much lower brittleness than CMCs; greater transverse stiffness and strength, and higher thermal and electrical conductivity if compared to PMCs), MMCs are used not only in the aerospace sector (62 per cent of world shipments measured in value and 14 per cent in weight) but also in the automotive (the corresponding figures are 33 and 83 per cent) and recreation (around 2 per cent in both cases) industries.[11] On the other hand, the value of their worldwide shipments remains quite marginal (around 60 MUSD in 1993). This may be explained by their lower ductility and toughness, the different rates of thermal expansion of the reinforcement and of the metal matrix, the fact that some MMCs may be subject to galvanic corrosion and finally because fiber-reinforced MMCs remain expensive materials.

Impact on metal and mineral producing countries

Given this analysis of the shipments of advanced materials by end-use markets, what is their impact on the use of more conventional metals and of course on the mineral and metal sectors of their producing countries? As one may imagine, measuring the impact of advanced materials on the conventional metal markets remains an almost impossible task since as suggested by Tilton material-for-material substitution (a new material replacing an older one on a weight-for-weight basis) is only one of the various types of substitution one must take into account.[12] The introduction of new materials may also result in the redesign of products, the birth of new ones or in a substantial change in market size of the product. In these cases, consumption of conventional metals may be affected by advances in technology which allows a product to be made with less material; by the increase in nonmaterial inputs such as labor, capital or energy; or by a change in the mix of goods used to satisfy a given need. Even if such an in-depth analysis is not yet available, some general conclusions and tendencies seem to emerge from the preceding sections, in particular concerning the material-for-material substitution.

First, up to now the impact of advanced materials on the use of more traditional metals has been much smaller than expected at the end of the 80's. The adoption of the advanced metals has been limited to the aerospace industry. Even if the shipments of MMCs are more diversified, their total value or volume remains quite limited. Electronic ceramics still represent the largest segment (73 per cent) of the advanced ceramics industry while the structural ceramics (the more threatening from the traditional metals point of view) still represent, for the reasons given above, a more fragmented and less mature market. PMCs represent the only exception to this general trend even though their success has been limited to the aerospace and recreational industries. In the former case, PMCs are displacing aluminum used for the "skin" of few new military aircraft (the expected large inroads of PMCs in passenger airliner manufacturing may not materialize before the middle of the next decade). In the latter market, their past performance will be sustainable only if a decline in price permits a greater penetration of the larger volume markets (recall that the higher the price-elasticity of demand facing a group of producers, the lower their profit margins). The outcome of materials competition in the large volume automotive industry is far from decided particularly in the production of body-panels. Several major car makers (notably Ford and Honda) have already made commitments to the development of aluminum exteriors.

Second, even if the economic impact of advanced materials on the markets of more traditional metal producers seems rather modest in the short run, the situation may be quite different in the medium and long terms as technological breakthroughs will solve the technical problems still hampering a wider use of advanced materials. Their adoption by consumers may also be accelerated by an increase in the relative prices of metals or by new regulations on the environment. Mineral producing countries should therefore continue their monitoring of the advanced materials industry and evaluate on a permanent basis what niche of this industry they may want to occupy (production of fine powders or of advanced metals, development of process technologies, or even a partial diversification in some well-defined advanced materials where they may have a competitive advantage). A wait-and-see strategy may be dangerous for a mineral producing country because advanced materials are more than substances with special performance properties. They may represent in many end-use markets the actual media that diffuse new technologies through industrial economies. Failure to understand, absorb, and adapt to these rapid technological changes may further isolate traditional producers from emerging material markets. This may be particularly true for the mineral producing less-developed countries which may be left out of the future trends in manufacturing and therefore in an uncompetitive industrial position. Another reason for monitoring the advanced materials industry is the opportunities these materials may provide for improving mining and mineral-processing technology. Their use in remote-sensing devices, cutting tools, solid-state processors for robotic operations, and abrasion-resistant conveyor belts may also help them explore for, mine, process, and use minerals more efficiently.

Finally, it is quite obvious that less-developed mineral producing countries are not keeping pace with developments in the area of advanced materials. Most of them are rather struggling to understand the changes brought in by innovations in that field. Even if some governmental intervention may be useful to promote an efficient technology transfer (for example, by bringing together individual policy areas and by coordinating efforts in education, science and trade policies), this transfer is even more facilitated by an environment conducive to the free exchange and acquisition of knowledge. This environment should ideally consist of:[13]

- an appropriate legal framework (protecting intellectual property and conducive to the transfer and acquisition of knowledge from abroad);
- a financial framework conducive to a rapid turnover of new scientific discoveries into technological ventures and with the capability to provide patient money capable of enduring the time requirements normally associated with the maturation of technology developments;
- a competitive domestic and international trade in technology (developing countries may gain from rich-country R&D mainly through international trade: by importing from the latter, developing countries acquire higher-tech inputs that make their own industries more efficient; also, importers may be able to work out and then copy the technology developed by foreign firms; and less directly, companies do become better at developing new technology and imitating foreign methods since international trade forces their economies to become more efficient);[14]
- a free exchange of scientific and technical information among the governmental, academic and industrial parties (in particular mobility of skilled scientific and technical personnel); and
- engineering skills and infrastructure capable to scale up, interpret and test research developments and transfer these into commercial utilization.

Such an environment may not completely fill the actual technological gap between developed and developing countries, but at least that gap will not get bigger and wider.

Notes

1. Fraser, Barsotti and Rogish, 1988.
2. Curlee and Das, 1991.
3. Bureau of Mines, 1990.
4. Materials Edge, August 1992, p. 8.
5. Materials Edge, various issues.
6. Bureau of Mines, 1990, chap. 2.
7. Materials Edge, August 1992, p. 8.
8. Deckman 1993.
9. Bureau of Mines, 1990, p. 2.40.
10. Bureau of Mines, 1990, p. 2.6.
11. Kume, 1994; Rohatgi, 1991; Terry and Jones, 1990.
12. Tilton 1983, p.2.
13. Vergara, 1993, p. 98.
14. The Economist, March 18, 1993, p. 78.

Bibliography

Curlee, T.R. and S. Das (1991), "Advanced Materials: Information and Analysis Needs", *Resources Policy*, December, pp. 316-331.

Deckman, B.W. (1993), "Advanced Ceramics: Outlook for the '90s", *Ceramic Industry*, May, pp. 36-39.

Fraser, S., A. Barsotti and D. Rogish (1988), "Sorting Out Materials Issues", *Resources Policy*, March, pp. 3-20.

Kume, Y. (1994), "Metal Matrix Composites in Japan: Commercial Applications and Current Research", *SRI International-Business Intelligence Program*, D94-1821, 14 pages.

Materials Edge, *Industrial Minerals Division of Metal Bulletin*, London, various issues.

McDonough, W.J. (1994), *Advanced Materials 1992*, U.S. Department of the Interior, Bureau of mines, Washington, 57 pages.

Rohatgi, P. (1991), "Cast Aluminum-Matrix Composites for Automotive Applications", *Journal of Metals*, April, pp. 10-15.

Terry, B. and G. Jones (1990), *Metal-Matrix Composites: Current Developments and Future Trends in Industrial Research and Applications*, Elsevier Advanced Technology, Oxford, 154 pages.

The Economist, March 18, 1995, p. 78.

Tilton, J.E. (1983), *Materials Substitution: Lessons from Tin-Using Industries*, Resources for the Future Inc., Washington, pp. 1-11.

U.S. Bureau of Mines (1990), *The New Materials Society: Challenges and Opportunities*, vol.1, U.S. Department of the Interior, Washington.

U.S. Bureau of Mines (1994), *Mineral Commodity Summaries 1994*, U.S. Department of the Interior, Washington, 1994.

U.S. Bureau of Mines (1994), *Annual Report on Advanced Materials–1993 Data*, U.S. Department of the Interior, Washington, preliminary report.

Vergara, W. (1993), *The Materials Revolution: What Does It Mean For Developing Asia?*, World Bank Technical Paper Number 202, The World Bank, Washington, 120 pages. ■