Advanced Processing and Manufacturing Technologies for Structural and Multifunctional Materials IV
Contents

Preface ix
Introduction xi

GREEN MANUFACTURING AND SMART PROCESSING

Securing the Supply of Precious and Special Metals—The Need of Closing the Loop
Christian Hagelüken 3

Mechanical Properties of Cr-Si-N-O Thin Films Deposited by RF Reactive Unbalanced Magnetron Sputtering
Jun Shirahata, Tetsutaroh Ohor, Hiroki Asami, Tsuneo Suzuki, Tadachika Nakayama, Hisayuki Suematsu, and Koichi Niihara 15

Room-Temperature Deposition and Magneto-Optical Properties of Transparent Cobalt/Lead Zirconate Titanate (PZT) Nanocomposite Films by Aerosol Deposition
Jae-Hyuk Park and Jun Akedo 23

Influence of Dispersant on Rheology of Zirconia-Paraffin Feedstocks and Mechanical Properties of Micro Parts Fabricated via LPIM
Fatih A. Çetinel, Marcus Müller, Joachim Rögner, Werner Bauer, and Jürgen Hausse 31

ADVANCED COMPOSITE MANUFACTURING

Fiber-Reinforced Ceramic Matrix Composites Processed by a Hybrid Process Based on Chemical Vapor Infiltration, Slurry Impregnation and Spark Plasma Sintering
Jerome Magnant, René Pailier, Yann Le Petitcorps, Laurence Maille, Alain Guette, Jimmy Marthe, and Eric Philippe 47
<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing of the CMC Nose Cap for the Expert Spacecraft</td>
<td>59</td>
</tr>
<tr>
<td>Christian Zuber, Thomas Reimer, Kornelia Stubicar, Bernhard Heidenreich, and Hermann Hald</td>
<td></td>
</tr>
<tr>
<td>The Nature of Silicon Carbide Phases Developed from Different Carbonaceous Sources and Its Impact on the Microstructure of C/C-SiC Composites</td>
<td>73</td>
</tr>
<tr>
<td>Andrew Leatherbarrow and Houzheng Wu</td>
<td></td>
</tr>
<tr>
<td>Shaping Radiation Curable Colloidal Dispersions—From Polymer/Ceramic Fibers and Microspheres to Gradient Porosity Ceramic Bulk Materials</td>
<td>85</td>
</tr>
<tr>
<td>Yoram de Hazan, Maciek Wozniak, Judit Heinecke, Gregor Müller, Veronika Märkl, and Thomas Graule</td>
<td></td>
</tr>
<tr>
<td>Melt-Infiltration Processing of Titanium Carbide-Stainless Steel Cermets</td>
<td>97</td>
</tr>
<tr>
<td>Tyler Stewart, R. Bradley Collier, Zoheir N. Farhat, Georges J. Kipouros, and Kevin P. Plucknett</td>
<td></td>
</tr>
<tr>
<td>Oxidation Behavior of Zirconium Diboride-Silicon Carbide Composites</td>
<td>105</td>
</tr>
<tr>
<td>Ipek Akin, Filiz Cinar Sahin, Onuralp Yucel, and Gultekin Goller</td>
<td></td>
</tr>
<tr>
<td>RAPID PROCESSING</td>
<td></td>
</tr>
<tr>
<td>Nano-Crystalline Yttria Samaria Codoped Zirconia: Comparison of Electrical Conductivity of Microwave and Conventionally Sintered Samples</td>
<td>115</td>
</tr>
<tr>
<td>Soumyajit Koley, Abhijit Ghosh, Ashok Kumar Sahu, and Ashok Kumar Suri</td>
<td></td>
</tr>
<tr>
<td>Spark Plasma Sintering (FAST/SPS) of Novel Materials—Taking the Next Step Forward to Industrial Production</td>
<td>127</td>
</tr>
<tr>
<td>H. U. Kessel, J. Hennicke, R. Kirchner, and T. Kessel</td>
<td></td>
</tr>
<tr>
<td>Rapid Manufacturing of Ceramic Parts by Selective Laser Melting</td>
<td>137</td>
</tr>
<tr>
<td>Jan Wilkes, Yves-Christian Hagedorn, Sörn Ocylok, Wilhelm Meiners, and Konrad Wissenbach</td>
<td></td>
</tr>
<tr>
<td>JOINING AND MACHINING</td>
<td></td>
</tr>
<tr>
<td>Active Metal Brazing and Characterization of Brazed Joints between Silicon Carbide and Metallic Systems</td>
<td>151</td>
</tr>
<tr>
<td>Bryan P. Coddington, Rajiv Asthana, Michael C. Halbig, and Mrityunjay Singh</td>
<td></td>
</tr>
<tr>
<td>Joining of Silicon Nitride with Glass or Powder under Mechanical Pressure</td>
<td>163</td>
</tr>
<tr>
<td>Naoki Kondo, Hideki Hyuga, Takaaki Nagaoka, and Hideki Kita</td>
<td></td>
</tr>
</tbody>
</table>
Fabrication of Thermodynamic Crystals by Structural Joining 169
Soshu Kirihara, Yasunori Uehara, and Youhei Takinami

Effect of Various Factors on Interface Formation in Magnetic Pressure Seam Welding 175
Hisashi Serizawa, Isao Shibahara, Sherif Rashed, Hidekazu Murakawa, and Shinji Kumai

Production Environment Laser Assisted Machining of Silicon Nitride 183
Federico Sciammarella, Joe Santner, Jeff Staes, Richard Roberts, Frank Pfefferkorn, Stephen T. Gonczy, Stefan Kyselica, and Ricardo Deleon

NET SHAPE FORMING

Gelcasting of High Performance Carbide Ceramics with Larger Size/Complex Shape 197
Dongliang Jiang

Processing of Complex-Shaped Micro Parts by Reaction-Bonding and Sintering of Silicon Nitride 213
M. Müller, W. Bauer, R. Knitter, and J. Rögner

Thermoplastic Ceramic Injection Molding of Zirconia Toughened Alumina Components 223
F. Kern, M. Abou El-Ezz, and R. Gadow

Fabrication of Alumina Dental Crown Model with Biomimetic Structure by Using Stereolithography 239
Mitsuyori Suwa, Soshu Kirihara, and Taiji Sohmura

Author Index 247
The Fourth International Symposium on Advanced Processing and Manufacturing Technologies for Structural and Multifunctional Materials and Systems (APMT) was held during the 34th International Conference on Advanced Ceramics and Composites, in Daytona Beach, FL, January 24–29, 2010. The aim of this international symposium was to discuss global advances in the research and development of advanced processing and manufacturing technologies for a wide variety of non-oxide and oxide based structural ceramics, particulate and fiber reinforced composites, and multifunctional materials. A total of 96 papers, including invited talks, oral presentations, and posters, were presented from more than 10 countries (USA, Japan, Germany, France, Italy, Slovenia, Serbia, Belgium, Turkey, Sweden, Canada, China, Korea, India and Israel). The speakers represented universities, industry, and research laboratories.

This issue contains 25 invited and contributed papers, all peer reviewed according to the American Ceramic Society Review Process. The latest developments in processing and manufacturing technologies are covered, including green manufacturing, smart processing, advanced composite manufacturing, rapid processing, joining, machining, and net shape forming technologies. These papers discuss the most important aspects necessary for understanding and further development of processing and manufacturing of ceramic materials and systems.

The editors wish to extend their gratitude and appreciation to all the authors for their cooperation and contributions, to all the participants and session chairs for their time and efforts, and to all the reviewers for their valuable comments and suggestions. Financial support from the Engineering Ceramic Division and the American Ceramic Society is gratefully acknowledged. Thanks are due to the staff of the meetings and publication departments of the American Ceramic Society for their invaluable assistance.

We hope that this issue will serve as a useful reference for the researchers and
technologists working in the field of interested in processing and manufacturing of ceramic materials and systems.

Tatsuki Ohji, Nagoya, Japan
Mrityunjay Singh, Cleveland, USA
Introduction

This CESP issue represents papers that were submitted and approved for the proceedings of the 34th International Conference on Advanced Ceramics and Composites (ICACC), held January 24–29, 2010 in Daytona Beach, Florida. ICACC is the most prominent international meeting in the area of advanced structural, functional, and nanoscopic ceramics, composites, and other emerging ceramic materials and technologies. This prestigious conference has been organized by The American Ceramic Society’s (ACerS) Engineering Ceramics Division (ECD) since 1977.

The conference was organized into the following symposia and focused sessions:

Symposium 1  Mechanical Behavior and Performance of Ceramics and Composites
Symposium 2  Advanced Ceramic Coatings for Structural, Environmental, and Functional Applications
Symposium 3  7th International Symposium on Solid Oxide Fuel Cells (SOFC): Materials, Science, and Technology
Symposium 4  Armor Ceramics
Symposium 5  Next Generation Bioceramics
Symposium 6  International Symposium on Ceramics for Electric Energy Generation, Storage, and Distribution
Symposium 7  4th International Symposium on Nanostructured Materials and Nanocomposites: Development and Applications
Symposium 8  4th International Symposium on Advanced Processing and Manufacturing Technologies (APMT) for Structural and Multifunctional Materials and Systems
Symposium 9  Porous Ceramics: Novel Developments and Applications
Symposium 10 Thermal Management Materials and Technologies
Symposium 11 Advanced Sensor Technology, Developments and Applications
Focused Session 1  Geopolymers and other Inorganic Polymers  
Focused Session 2  Global Mineral Resources for Strategic and Emerging Technologies  
Focused Session 3  Computational Design, Modeling, Simulation and Characterization of Ceramics and Composites  
Focused Session 4  Nanolaminated Ternary Carbides and Nitrides (MAX Phases)  

The conference proceedings are published into 9 issues of the 2010 Ceramic Engineering and Science Proceedings (CESP); Volume 31, Issues 2–10, 2010 as outlined below:  

• Mechanical Properties and Performance of Engineering Ceramics and Composites V, CESP Volume 31, Issue 2 (includes papers from Symposium 1)  
• Advanced Ceramic Coatings and Interfaces V, Volume 31, Issue 3 (includes papers from Symposium 2)  
• Advances in Solid Oxide Fuel Cells VI, CESP Volume 31, Issue 4 (includes papers from Symposium 3)  
• Advances in Ceramic Armor VI, CESP Volume 31, Issue 5 (includes papers from Symposium 4)  
• Advances in Bioceramics and Porous Ceramics III, CESP Volume 31, Issue 6 (includes papers from Symposia 5 and 9)  
• Nanostructured Materials and Nanotechnology IV, CESP Volume 31, Issue 7 (includes papers from Symposium 7)  
• Advanced Processing and Manufacturing Technologies for Structural and Multifunctional Materials IV, CESP Volume 31, Issue 8 (includes papers from Symposium 8)  
• Advanced Materials for Sustainable Developments, CESP Volume 31, Issue 9 (includes papers from Symposia 6, 10, and 11)  
• Strategic Materials and Computational Design, CESP Volume 31, Issue 10 (includes papers from Focused Sessions 1, 3 and 4)  

The organization of the Daytona Beach meeting and the publication of these proceedings were possible thanks to the professional staff of ACerS and the tireless dedication of many ECD members. We would especially like to express our sincere thanks to the symposia organizers, session chairs, presenters and conference attendees, for their efforts and enthusiastic participation in the vibrant and cutting-edge conference.  


Sanjay Mathur and Tatsuki Ohji, Volume Editors  
July 2010
Green Manufacturing
and Smart Processing
ABSTRACT

Special and precious metals are key ingredients for high tech applications like information technology, electronics, or car-catalysts, and emerging clean technologies such as photovoltaics, fuel cells or electric car batteries. With a relatively recent use in mass applications, 80% or more of the cumulative mine production for e.g. the Platinum Group Metals (PGM), gallium, or indium took place just in the last 30 years.

A future sufficient access to these 'technology metals' is essential. Their primary production is often coupled to base metals and concentrated in few mining regions of the world, causing a complex demand-supply balance and high price volatility. Hence it is necessary to secure their resource efficient use along the lifecycle and to establish effective recycling systems to "close the loop", preserving limited resources. Appropriate management at the product's end-of-life however is challenging. Most consumer products are characterized by an "open cycle" with non transparent global flows and multiple owners along the lifecycle, a complex material composition, and demanding collection and recycling chains.

The contribution addresses these issues from a holistic perspective and elaborates the system interdependencies and potential ways of improvement. On the example of precious metals it will be shown that in many cases effective recycling technologies exist but that the majority of consumer products do not enter in such recycling chains so far.*

INTRODUCTION

Metals are classical examples of non-renewable resources, and their extraction from Earth by mining of ores cannot be seen as sustainable in the strict sense of the word. Mining, by definition, depletes the ore reserves. Through mineral processing and subsequent smelting and refining, ores are disintegrated, and the desired metals are isolated for use in the technosphere. Special and precious metals play a key role in modern societies as they are of specific importance for clean technologies and other high tech equipment. Important applications are information technology (IT), consumer electronics, as well as sustainable energy production such as photovoltaic (PV), wind turbines, fuel cells and batteries for hybrid or electric cars. They are crucial for more efficient energy production (in steam turbines), for lower environmental impact of transport (jet engines, car catalysts, particulate filters, sensors, control electronics), for improved process efficiency (catalysts, heat exchangers), and in medical and pharmaceutical applications. Figure 1 provides an overview of these main applications areas for selected metals and illustrates their significance for modern life. For example, electronic products can contain up to 60 different elements and in their entity are major demand drivers for precious and special metals: Just the annual sales of mobile phones and computers account e.g. for about 3% of the world mine production of gold and silver, 15% of palladium and over 20% of cobalt.1

Driving forces for the booming use of these "technology metals" (used here as a synonym for precious and special metals) are their extraordinary and sometimes exclusive properties, which make...
many of these metals essential components in a broad range of applications. Building a more sustainable society with the help of technology hence depends to a large extent on sufficient access to technology metals.

POTENTIAL METAL SCARCITIES AND SECURITY OF SUPPLY

In the context of raising metal prices and the boom in demand for many technology metals, a discussion on potential metal scarcities restarted about 4 years ago. More than 30 years after the Club of Rome’s “The Limits to Growth” publication from 1972, it put again more emphasis on the finite character of our natural resources, a debate which had calmed down for almost two decades in between. Since the 1970s, a lot has happened specifically with respect to the use of the “technology metals”. 80% or more of the cumulative mine production of platinum group metals (PGM), gallium, indium, rare earth elements, and silicon, for example, has occurred over the last 30 years. For most other special metals, more than 50% of their use took place in this period, and even for the “ancient metals” gold and silver use from 1978 onward accounts for over 30% (Fig. 2). In many cases the booming demand especially from consumer mass applications drove up metal prices significantly. For example, the significant increase in demand of platinum and palladium was mainly caused by automotive catalysts (50% of today’s platinum/palladium demand) and electronics (Fig. 3). So more often the question is raised: “How soon will we run out of key element resources?” and occasionally: “Are severe shortages of certain critical metals within the next decade threatening?” Governments in the US, Japan and since recently also in Europe undertake efforts to define which metallic resources are specifically critical for their economies and which measures should be taken to improve their long-term supply security.
Securing the Supply of Precious and Special Metals—The Need of Closing the Loop

Figure 2: Share of technology metals mined since 1978 compared to cumulated production between 1900-2007; copper and nickel included for comparison (modified after 2).

Figure 3: Long term development of demand and nominal prices for platinum (Pt) and palladium (Pd)

The current debate takes place between two extremes - resource optimists versus resource pessimists. Optimists argue that in principal market mechanisms will help to overcome supply shortages. Increased metal prices will lead to new exploration and mining (of so far uneconomic deposits) and technical substitution will be able to replace scarce metals by others with similar properties, or by thrifting and innovative technologies. Pessimists start with information about ore
resources, compiled by the US Geological Services (USGS)\(^8\) among others, and then divide these numbers by the current and projected annual demand. For some metals such as indium this leads indeed to rather short “static lifetimes”. While the scientific debate is open to the many facets of the matter, media sometimes tend to bring this in rather black and white statements. This contribution follows a pragmatic “resource realist” approach, without diving into detailed discussions on statistics and single metals. The aim is to discuss the main parameters and mechanisms that impact metal scarcities and what can be done to prevent them.

**DIMENSIONS OF RESOURCE SCARCITY**

Three types need to be distinguished, namely absolute, temporary and structural resource scarcity, and in this context the understanding of the primary supply chain is crucial.\(^2\)

**Absolute scarcity** would mean the depletion of economically mineable ore resources. In this case all ore deposits of a certain metal — including the ones which have not yet been discovered by exploration — would have been widely mined out, and the total market demand for a metal would exceed the remaining mine production. This would first lead to extreme price increases and finally force substitution of that metal (or technology) in certain applications, or would put severe limits to the further technology distribution (as worst case a good technology, e.g. for energy generation, is endangered because a key metal is not available). However, within the foreseeable future such an absolute scarcity is rather unlikely, and here the arguments of the resource optimists count. Extremely high prices would make deep level mining and mining of low grade deposits, which are currently left aside, economically feasible. Also it would trigger more exploration, leading to the discovery of new ore bodies. Exploration is very costly and time consuming, so as long as mining companies have enough accessible deposits for the next two decades there is not much incentive for them to conduct additional exploration. Accordingly, the data reported by USGS\(^8\) and other geological services do not report the absolute availability of metals on the planet but compile the known deposits that can be extracted economically already today (reserves), or where it is expected to be potentially feasible (resources). If exploration and mining efforts extent deeper into the earth’s crust or oceans and cover a wider geographical area, maybe even into arctic regions, substantial new metal resources are very likely to be accessible, however this will not come without trade offs as we will see below\(^9\).

In contrast, **temporary or relative scarcity** is a phenomenon which has been already experienced. In this case, metal supply is for a certain period in time not able to meet the demand. Reasons can be manifold. New technological developments, strong market growth in existing applications, or speculative buying of investors can drive up the demand significantly within a short time so that mine supply lags behind. Also the supply can be disrupted by political developments, armed conflicts, natural disasters or other constraints in the mining countries itself, within the transport of ore concentrates, or also at major smelters/refineries. Temporary scarcities are a main reason for the sometimes extreme price volatility in metal markets. The risk on temporary scarcities increases with increasing concentration of the major mines or smelters in few and/or unstable regions, or in few companies. Also a low number of applications in which the metal is used increases the risk. Often, different factors come together and then accelerate the development. For instance, in the first quarter of 2008 a soaring demand for PGMs from automotive catalysts and (speculative) investment coincided with a reduced supply from South African mines due to shortages in electric power. The prices of platinum and rhodium went to record heights within a short time as South Africa produces over 75% of platinum and rhodium supply.

Speculation about potential depletion of indium resources started when from 2003 onwards the sales boom of LCD devices (monitors, TVs, mobile phones etc), which use indium-tin oxide (ITO) as
transparent conductive layer, drove up indium prices significantly. The development of indium prices (Fig. 4) is a good example to illustrate the effect of temporary scarcities. The supply could not follow the sudden jump in demand and indium prices went up by factor 10 between 2003 and 2006. An important impact on this development has the manufacturing technology used for LCD applications, which is a sputter process. From the indium contained in the ITO targets, less than 20% end up as conductive layer on LCD screens, while the rest goes into production scrap at various stages of the process. Hence the gross indium demand is significantly higher than what is finally used for the product. The production scrap, however, is not lost, the biggest part of it are spent targets which can be recycled very efficiently. With the limited recycling capacities available before the boom, the huge new scrap arising could not be handled. But due to the increasing indium prices, recycling became attractive, spent targets were stockpiled, and new recycling capacities were build up. After 2006 an increased primary supply (also triggered by higher prices) and a significant secondary supply (working down the target stockpiles) drove down the indium prices again, which was further amplified end of 2008 by the economic crisis. It is important to understand that the high recycling rates (> 50%) reported for indium only refer to this recycling of high grade production scrap. So far, hardly any indium recycling takes place for end-of-life products, which will be much more challenging from a technical and economic point of view (the In concentration in the final product is very low). It can be assumed that in the meantime sufficient recycling capacity for production scrap is available and that the stocks have been largely eaten up. Hence, a further increase in indium demand, supported as well by thin film solar cells, is likely to drive up the prices again. On the long run, for the indium supply the structural scarcity as described below will become an important factor (In is a by-product from zinc mining).

In future, a take off in thin film photovoltaics would boost the demand for tellurium, indium, selenium, and gallium, mass applications of electric vehicles will require large amounts of lithium, cobalt and some rare earth elements, and fuel cell cars would need significantly more platinum than is used today in a catalytic converter. Developing and expanding mining and smelting capacities is highly capital intensive, risky, and it takes many years to materialize. Hence, temporary scarcities are likely to happen more often in future.

![Figure 4: Development of indium prices (monthly averages) since 1988](image)
The structural scarcity is most severe for many technology metals, which are often not mined on their own but occur only as by-products from so-called major or carrier metals. Indium and germanium, for example, are mainly by-products from zinc mining, gallium from aluminum, and selenium, tellurium from copper (and lead). The PGMs occur as by-products from nickel- and copper mines, and as coupled products in own mines. Within the PGMs ruthenium and iridium are by-products from platinum and palladium (Fig. 5). Since the by-product ("minor metal") is only a very small fraction of the carrier metal, here the usual market mechanisms do not work. An increasing demand will certainly lead to an increasing price of the by-product metal, but as long as the demand of the major metal does not rise correspondingly, mining companies will not produce more, because this would erode the major metal's price. In this respect, the supply of by-product metals is price-inelastic, even a "ten-fold increase" in its price could usually not compensate the negative impact on total revenues when there is oversupply of the major metal. Moreover, many technology metals are important ingredients for several emerging technologies simultaneously (Fig. 1), so a competition between applications becomes likely and increasing demand from various segments will intensify the pressure on supply.

Substitution is not likely to become the solution for many of these metals either since the required functional properties can often be met only by metals from the same metal family. For example, substituting platinum by palladium in catalytic applications will just shift the problem from one temporary/structural scarce metal to the other, which was experienced in the second half of the 1990s, pushing the before cheaper palladium to record heights in 2000/2001 (Fig. 3). In emerging opto-electronics the crucial metals are silicon, tellurium, gallium, selenium, germanium, and indium. They can partially substitute each other, though this will not really mitigate the problem (Fig. 6). It can only be overcome by increasing the efficiencies in the primary supply chain (possibly leading to considerable gains) and, above all, by comprehensive recycling efforts as pointed out hereafter. Omitting the fact that many technology metals are by-products and that structural scarcity is possible is thus the weak point in the resource optimists’ argumentation.
Securing the Supply of Precious and Special Metals—The Need of Closing the Loop

Independent of whether or not supply constraints are likely, the impact of mining of lower grade ores and from more challenging locations must not be overlooked. It will inevitably lead to increasing costs, energy demand, and raising emissions, it will impact the biosphere (rain forest, arctic regions, oceans), and it can increase the dependence on certain regions ("battle for resources"). This can imply significant constraints on emerging technologies, unless effective life cycle management enables the use of recycled (secondary) metals in the forthcoming years.

THE NEED OF CLOSING THE LOOP

Metals are not consumed, they are only transferred from one manifestation into another, moving in and between the lithosphere and the technosphere. Thus the latter becomes our future 'renewable' resource in society. Thoroughly extracting "urban mines" is the only sustainable solution to overcome supply disruptions. Metal combinations in products often differ from those in primary deposits, which results in new technological challenges for their efficient recovery. In products such as electronics or catalysts, the precious metals (Au, Pt, Pd, ...) have become the economic drivers for recycling ("paying metals"), while many special metals (Se, Te, In, ...) can be recovered as by-products when state-of-the art treatment and refining operations are used. Very low concentration of technology metals in certain products or dissipation during product use sets economic and technical limits in many cases, and technical challenges exist especially for complex products like vehicles, computers, etc. Effective recycling requires a well tuned recycling chain, consisting of different specialized stakeholders: Starting with collection of old products, followed by sorting/dismantling and preprocessing of relevant fractions, and finally recovery of technology metals. The latter requires sophisticated, large scale metallurgical operations like the Umicore integrated smelter-refinery in Antwerp, Belgium where currently seven precious metals (Ag, Au, Pt, Pd, Rh, Ru, Ir), as well as eleven base and special metals (Cu, Pb, Ni, Sn, Bi, As, Sb, Se, Te, In, Ga) are recovered and supplied back to the market. Most of these metals are recovered with high yields, in the case of the precious metals yields are well over 95% of what was contained in the feed material to the plant. The plant input of approximately 1000 metric tons per day comprises over 200 different categories, the majority of which consists of recyclables (car catalysts, various process catalysts, cell phones, circuit boards, photographic residues, fuel cells, etc.) and smelter by-products (slags, flue dust, anode slimes, effluent treatment sludges, etc.).
Recycling technology has made significant progress and further improvements extending the range and yield of metals are underway. When required, recycling technologies are adapted to new products, as has been successfully the case e.g. for certain petrochemical process catalysts, fuel cells, diesel particulate filters, or high grade residues from thin film solar cell manufacturing. Design for sustainability based on a close dialogue between manufacturers and recyclers can further support effective recycling as it starts already in the design and manufacturing phase and proceeds all along its lifecycle.

However, the biggest challenge to overcome is the insufficient collection of consumer goods, and inefficient handling within the recycling chain. As long as goods are discarded with household waste, stored in basements or ending up in environmentally unsound recycling operations, the total recovery rates will remain disappointingly low, as it is the case today for most consumer goods. Legislation can be supportive but monitoring of the recycling chain as well as tight enforcement of the regulations are crucial for success. For example, in spite of a comprehensive European legislative framework (“Directive on waste electrical and electronic equipment/WEEE-Directive”; “Directive on end-of-life vehicles/ELV Directive”), a significant share of end-of-life computer, cell phones, cars, etc. are currently not recycled properly. Instead they are discarded or (illegally) exported to Asia or Africa under the pretext of “reuse” to circumvent the Basel Convention regulations on transboundary shipments of waste. The same happens in North America and Japan. This leads to a situation where state-of-the-art, high financial investment recycling facilities in industrialized countries are underutilized because ‘recycling’ and the associated environmental burden of environmentally unsound treatment is ‘outsourced’ to the developing world. Except some inefficient gold and copper recovery, technology metals are lost in such primitive “backyard recycling processes”, the “urban mine is wasted irreversibly.”

A striking example is the automotive catalyst. Due to the high prices of the contained PGMs platinum, palladium and rhodium its recycling is economically highly attractive (several tens of US-dollars per piece paid to the scrap yard). An autocatalyst is easy to identify and remove from an end-of-life car, a comprehensive collection infrastructure exists, and state-of-the-art metallurgical treatment operations achieve PGM recovery yields of 98%. Nevertheless, on a global scale only about 50% of the PGMs originally used for automotive catalysts are finally recovered, the rest is lost inevitably. The main reasons are global flows of end-of-life cars (e.g. in Germany from a little over 3 million annual car deregistrations only about 0.5 million cars are recycled within Germany, the remainder is exported largely out of Europe) and a high degree of intransparency and “informal” business practices in the early parts of the recycling chain (even in industrialized countries). Figure 7b shows the typical structure of so called “open cycles” for consumer goods. The insufficient cooperation along the life cycle and recycling chain (although “extended producer responsibility” has been implemented), combined with insufficient tracking of product and material streams along the entire chain explain why inefficient open cycles continue to exist.

To effectively close the loop for consumer products, new business models need to be introduced that provide strong incentives to hand in products at their end-of-life into professional recycling systems. This can include deposit fees on new products, or product service systems (PSS) like leasing or other approaches. Especially for emerging technologies (electric vehicles, fuel cells, photovoltaics etc.) setting up “closed loop structures” will be essential and manufacturers who put successful models in place can thus secure their own supply of technology metals in the future.

Such closed loop structures exist successfully already in most industrial applications of precious metals. For example, PGM-catalysts used in fine chemistry or oil refining are turned around very efficiently at their end of life. Usually well over 90% of the PGMs used in the fresh catalysts are finally recovered, even at long catalyst use times (up to 10 years in some applications), several
Securing the Supply of Precious and Special Metals—The Need of Closing the Loop

regeneration cycles, and difficult operating conditions in the chemical reactor or oil refinery. The metallurgical steps to recover the PGMs from the spent catalysts are similar to the ones used for automotive catalysts. The decisive differences lie in the lifecycle structure and the steps prior to metallurgical recovery. Here, for industrial process catalysts the complete lifecycle in handled very transparently in a highly professional way between the industrial actors involved (Fig. 7a). Catalyst manufacturers, users, and recyclers work closely together, the location of the catalyst is always well defined, and a profound knowledge exists about the properties and use history of a specific catalyst. Usually catalyst users (e.g. chemical plants) maintain the property of the PGMs throughout the entire lifecycle. Recycling is contracted with a precious metals refinery as a “toll refining operation” with a physical credit of the PGMs back to the user who provides them directly to a catalyst manufacturer for the production of a fresh catalyst. From there, a new lifecycle starts. As a consequence, the net demand for PGMs from the (petro)chemical industry as a whole is just below 10% of the total global PGM net demand. It is used to cover market growth, new application and the small losses that occurred during the catalyst lifecycle. The gross demand, however, i.e. the annual new use of PGMs for process catalysts, is as high as for automotive catalysts, but the latter makes up for about 50% of the global PGM net demand. A transformation of “open cycles” in consumer applications into “closed cycles” as prevail in many industrial applications would be a big step towards a secured supply of technology metals.

Figure 7: (a) Closed loop systems for industrial applications (example process catalyst) versus (b) Open loop systems for consumer goods (example consumer electronics)
CONCLUSION

In an ideal system, the sustainable use of metals could indeed be achieved by avoiding spillage during each phase of the product life cycle. As illustrated in figure 8, such losses occur at various stages and it needs to analyze the specific impact factors to identify the most appropriate means for each stage. It is important to understand that universal means to improve recycling do not exist, if material properties or technology constraints have the main impact, then completely different measures will be required than if societal or life cycle issues are the main loss driver. Mining and recycling thus need to evolve as a complimentary system, where the primary metals supply is widely used to cover inevitable life cycle losses and market growth, and secondary metals from end-of-life products contribute increasingly to the basic supply. Effective recycling systems would thus make a significant contribution to conserve natural resources of scarce metals and secure sufficient supply of technology metals for future generations.

It would further mitigate the climate impacts of metal production, which is energy intensive, especially in the case of precious metals mined from low concentrated ores (e.g. Au mined at 5 g/t from 3000 m underground). The mining of annually 2500 t of gold worldwide generates some 17,000 t of CO_2 per ton of gold produced (based on ecoinvent 2.0 database of EMPA/ETH Zurich), or 42 million tons CO_2 in total. For PGMs the ore grade and specific CO_2 impact is in the same magnitude, while copper mining “only” causes 3.5 t CO_2/t Cu, but adding up to 56 million tons at production of 16 million tons annually. Some mass products are relatively rich “bonanzas” in comparison, e.g., a computer motherboard with ca. 250 g/t of gold, a mobile phone handset with 350 g Au/t, or an automotive catalytic converter with some 700 g/t of PGM. If effective collection systems and state-of-
the-art recovery processes are used, the secondary metal production from such products requires only a small fraction of energy/CO₂ compared to mining.¹²

Such products carry a high intrinsic metal value which makes recycling attractive under an economical point of view as well. Recovering pure metals from a PC circuit board costs only about 20% of its intrinsic metal value, leaving sufficient margins to pay for logistics and dismantling, in case of car catalysts the cost share is even less. This similarly applies for large multi-metal products such as cars. But for other technology metals containing products like TVs, audio equipment and household appliances, the intrinsic metal value is usually not sufficient to pay the total costs of the recycling chain, and incentives by legislation, manufacturers, or distributors are needed for stimulation. However, if the true costs of landfill and environmental damage caused by non-recycling would be accounted for, then on a macroeconomic level proper recycling most probably is viable for such products as well. In this sense efficiently recycling our end-of-life products today is insurance for the future: It will prevent/smoothen metal price surges and secure a sustainable and affordable supply of metals needed for our products of tomorrow.

FOOTNOTE

The article is an updated and extended version of a contribution by the author entitled “Precious Element Resources” to the McGraw-Hill 2010 Yearbook of Science & Technology.

REFERENCES

⁵M. Wolfensberger, D. Lang, R. Scholz, (Re)structuring the field of non-energy mineral resource scarcity. ETH working paper 43. ETH Zürich: R. Scholz, Natural and Social Science Interface (NSSI) (2008).