Proposal for ATP Focused Program: Tools for Engineered Surfaces

NOTE: *From 1994-1998, the bulk of ATP funding was applied to specific focused program areas—multi-year efforts aimed at achieving specific technology and business goals as defined by industry. ATP revised its competition model in 1999 and opened Competitions to all areas of technology. For more information on previously funded ATP Focused Programs, visit our website at http://www.atp.nist.gov/atp/focusprg.htm.*

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Executive Summary

The ATP Focused Program, **Tools for Engineered Surfaces**, is being proposed to help industry overcome several high-risk technical barriers and make a paradigm shift from a point solutions approach to a structured approach in the development of new materials, processes, or components. The goal of this program will be to (1) simultaneously improve engineered surface process designs and reduce cost through reduced development time and increased yield and consistency; and (2) develop prime reliant surfaces which are integral to the design and operation of a component, as opposed to mere life enhancement. The strategy for meeting that goal will be the development of a set of manufacturing and analytical process tools which are applicable to materials which provide wear, corrosion and thermal enhancements to substrates, and which exploit new developments in process diagnostics (including in-line process control and non-destructive evaluation); life / performance prediction (including innovative modeling and simulation); and equipment design and development.

Definitions

Tool: a means of specifying, tailoring, designing, monitoring, or controlling the modification of a surface to produce a component with predictable properties and performance

Surface engineering: the design and modification of the surface and substrate together, as a system, to give cost-effective performance enhancement of which neither is capable on its own

Point solution: solution which is applicable for a single case which cannot be easily applied to a new situation

Prime reliancy: provide its function in a reliable, predictable way, for the full life of the component

Opportunity being addressed

Engineered surfaces are critical to the performance of many commercial products. Contact with industry and academia in the Surface Engineering community has suggested that, due to individual priorities and availability of resources, today's approach to surface development tends to be empirical and specific to a component and/or materials system. As a result, industrial knowledge consists of sets of point solutions--this has made it difficult to develop new opportunities that are not very similar to a previous application, since the more general problems of process design and scale-up, performance prediction and material development, have not been addressed. Our discussions and working group meetings with the surface engineering community would suggest that an ATP focused program in surface engineering should offer the opportunity to shift the industry from point solutions to a structured approach, ultimately moving the status of surface modification from life enhancement to prime reliancy.

Background

Engineered surfaces are critical to the performance of many commercial products. For example, most of the components in a typical jet engine or motor vehicle are surface engineered in some manner, whether through heat treating, texturing, coatings, or some other form of surface engineering. The vast majority of engineered surfaces are developed empirically for specific components and materials, and tend to represent an incremental improvement. A few of the processes involved to fabricate these engineered surfaces include chemical vapor deposition (CVD), physical vapor deposition (PVD), plasma spray, and ion implantation. Material examples include diamond films for cutting tools, titanium nitride on wear surfaces, and zirconia thermal barrier coatings on turbine blades.

Potential for U.S. Economic Benefit

Potential benefits from engineered surfaces are very wide spread since they affect almost all industries to some extent. Several representative industries in which engineered surfaces are critical are listed in Table I. For these industries, the total value of 1995 product shipments was $524.56B, with a total of 9,524 establishments with 1,458,200 employees. Table II indicates that these industries consume almost $25B in materials, a significant percentage of which are surface engineered. Table III lists several supporting industries, with a total value of product shipments of $35.23B in 1995.

In addition to those industries listed in Table I, other large industries also employ engineered surfaces, such as printing, textiles, and pulp and paper.

In order to determine the potential benefits of technical success in an engineered surfaces program, one would consider both the effect on the products listed above, as well as the effects on the markets for the coatings themselves. Some information on just a few coating techniques is shown in Table IV. These are values of worldwide shipments, which indicate that the worldwide values for CVD, PVD, implantation, and epitaxy coatings was $8.7B, projected to grow to $15.2B by 2000. It should be noted that a significant percentage of this market is controlled overseas. According to BCC, Inc., the value of the U.S. ceramic coatings (materials only) market is $564M, with an annual growth rate of 7.4%.

Battelle Laboratories performed a 1995 update of a 1978 NBS study on the cost of metallic corrosion in the U.S.--they estimated this at $300B/year (4.2% of GNP). Of this amount, $104B was considered avoidable. Studies have also been performed on the cost of wear to the U.S.--two examples are cutting tool wear at $900M/yr (in 1975 dollars) and automotive maintenance and repair (much of which can be attributed to wear) at $40B/year (in 1975 dollars)--the cost of wear today is in the neighborhood of the cost of corrosion. Engineered surfaces are key to the reduction of avoidable corrosion and wear. A focused program in tools for engineered surfaces will enable a dual path--on the earlier path, current material systems will gain increased performance and reliability; on the later path, the knowledge base for the development of new and better systems to combat corrosion (or other issues) will be built.

Table I. Representative U.S. Markets that depend on Engineered Surfaces

	Value of U.S. Product Shipments, 1995, $M	No. of establishments*	No. of Employees*
Motor Vehicles, Car Bodies, Parts, Accessories	303,280.1	3702	628,000
Construction, Mining, Oil & Gas Field Machinery, Farm Equipment	56,169.6	3425	178,000
Turbines, Generator Sets, IC Engines	22,681.0	373	83,700
Aircraft, Aircraft Engines, Parts, Equipment	137896.5	1745	546,900
Heat Exchangers, Steam Condensers.	2636.3	216	21,000
Bone Plates, Screws, Artificial Joints	1896.5	63	

***Source**: DOC Bureau of Census, 1995 Annual Survey of Manufactures, *1992 Census of Manufactures*

Table II. Materials Consumed by Representative Industries in Table I, $M

Engines	20,670.5
Hydraulics, Pneumatic Fluid Power Pumps, Motors, Hydrostation Transmissions	1171.0
Hydraulic Cylinders and Actuators	490.46

Speed Changers, Gears, High Speed Drives	400.7
Bearings	1303.9
Cutting Tools for Machine Tools	265.6
Car Bodies	662.9

Source: DOC Bureau of Census, 1992 Census of Manufactures

Table III. Representative U.S. Supporting Industries for Engineered Surfaces

	Value of U.S. Product Shipments, 1995, $M	No. of establishments	No. of Employees
Fluid Power Cylinders and Actuators	2201.0	348	16,500
Fluid Power Pumps and Meters	2021.6	176	12,400
Industrial Machinery	26,868.6	22,756	183
Ball and Roller Bearings	4138.8*	183	34,900

Source: DOC Bureau of Census, 1995 Annual Survey of Manufactures, *1992 Census of Manufactures

Table IV. A Representation of Values of Worldwide Shipments on Coatings

Coating Process	Value of Worldwide Shipments, 1995	Projected Annual Growth	Est. Value of Product Shipments, 2000
CVD Equipment	$2.6B	12.2%	$4.7B
CVD Materials	$347M	12.5%	$626M
CVD Services	$449M	9.2%	$697M
PVD Equipment	$2.7B	11.5%	$4.7B
PVD Materials	$335M	11.6%	$581M
PVD Services	$567M	8.5%	$850M
Implantation and Epitaxy Equipment	$1.4B	11.7%	$2.5B
Implantation and Epitaxy Materials	$128M	11.2%	$219M
Implantation and Epitaxy Services	$192.5M	8.8%	$292.5M

***Source**: BCC, Inc. Thin Layer Deposition Technologies, 1996*

Good Technical Ideas

Successful proposals will present high risk innovative approaches to the development of tools for engineered surfaces, all with the larger goal of reduced cost and greater performance (through greater reliability, uniformity, and batch-to-batch consistency) shorter development time, and prime reliancy. Some of the general areas within which solutions may be developed include plasma diagnostics, in-situ monitoring and control, structure-function modeling, simulations and prediction, scalability of design, controlled low temperature or atmospheric processing, non-destructive evaluation, improved torches, and others. A few examples of innovative ideas follow.

Process Diagnostics: Point of Deposition Monitors, Controls, and Models

The understanding of processes, in-situ, is extremely important in being able to develop consistency and reliability over time in a product. Sophisticated plasma diagnostics are now being developed and could aid in this endeavor. The development of on-deposit sensors based on the intrinsic response of complex oxides (such as perovskites) to temperature, stress and environment offers the potential to measure critical parameters. These sensing elements may be imbedded in solid prototypes of actual components to be coated or produced as printed circuits on test substrates. They may also be developed as "witness" condition sensors--a novel concept to measure conditions at the site of deposition without interfering with the deposition site itself. Research required includes determination of appropriate oxide compositions, understanding of response to deposition parameters, and methods of fabrication and data handling in cost-effective ways. The verification of process models which allow scale up is critical to evolution of models as well as development of credibility which ensures their use. Positron emission monitoring of reactive species distribution demonstrated in catalytic system design in universities in the United Kingdom and the Netherlands may provide such a means but has been unproven at elevated temperatures.

The cleanliness of a surface is only now beginning to be understood, yet it has a profound effect on the performance of a coating. An innovative cleanliness monitor has been theorized which could be developed by using plasma to excite species on the surface--wavelength emissions could yield information about the conditions. A study of this nature would also include a definition of sufficiently "clean."

Interfaces are being tailored by utilizing dual plasma sources (concurrent processes) to control the distribution of heat input during processing. The functions of the plasma would be separated, one providing heat for deposit chemistry control and the other to heat the substrate (and to change the structure of the boundary layer).

Equipment Design: Plasma Spray Torch Design

More precise control will be needed in order to significantly increase the reliability and uniformity of coating. Significant aspects of torch design which are limitations to control and process repeatability include understanding of the behavior of injected coating materials and electrode erosion prediction and control. The key to improvement lies in the ability to model and measure the three dimensional time dependent behavior of these high temperature, turbulent systems.

A general model applicable to all torch manufacturers has been called for and would allow the rapid introduction of new processes, such as high rate deposition of nano materials. For example, hypersonic plasma particle deposition, HPPD, involves the feeding of reactants into a plasma, and the formation of nanoparticles. This process has a deposition rate of 1 um/second and is potentially useful for the formation of nanostructured surfaces, as well as freeform fabrication. Feasibility has been demonstrated, but consistent, uniform coatings with sufficient film adhesion or wear resistance have not been fabricated.

Life / Performance Prediction

The performance of engineered surfaces to allow transition from being a performance enhancement to a reliable part of a component requires predictive tools which relate processing to properties to performance. The methodology for this has been initiated for gear steels. These monolithic models are less complex than the bi-material engineered surface systems which typically include metastable, anisotropic materials. Models which range from atomistic to continuum features are being considered in finite element analysis (FEA) designs used by the engineering community. Conceptual approaches and the isotropic models provide a starting point.

Strong Commitment of Industry

The ATP currently has a portfolio of industry-led projects involving engineered surfaces. Including several General Competitions and two focused program solicitations, *Materials Processing for Heavy Manufacturing* and *Motor Vehicle Manufacturing Technology*, ATP currently supports 9 industry-led engineered surfaces projects with estimated funding of over $25 million which leverages over $27 million of cost-shared industry funds committed over 2-5 years. As may be seen in Table V, projects which began before 1995 concentrate on materials developments. In 1995, the emphasis not only included the materials development, but began to integrate the concept of tools. This program will continue this trend with an emphasis on their use to achieve the goal of prime reliancy.

Table V. Summary of Previous ATP Awards in the area of Surface Engineering

Material / Process / Start Year	Innovation	Significant Use of Tools?
Functionally Gradient Materials: Ceramic Coatings (1993)	Combination of processes for new family of materials	No
CVD Diamond on Cutting tools (2 projects) (1993, 1994)	Optimizing materials properties such as adhesion	No
Polymer films to replace paint on aircraft (1994)	Materials development	No
Engineered Surfaces: Ceramic, DLC Coatings and Textures (1994)	Tailored coatings to specific applications such as gears	Not main emphasis, but some measurement tools were key
Plasma source ion implantation for wear (1995)	Materials development	No

Diamond-like nanocomposite films for wear and corrosion (1995)	Diagnostic techniques to better understand the process and thus optimize it	Yes
Linear magnetron sputtering for TiN and CrN on thin walled cylindrical objects (1995)	Development of equipment to control the deposition of these materials	Yes
ZrO_2 Thermal Barrier Coatings (1995)	Suite of sensors, models and controls for process control	Yes

The ATP team has also spoken to approximately 60 companies, universities, and laboratories, all of whom felt an ATP program in Engineered Surfaces would be both appropriate and important. The working group has 53 members. There have been 2 working group meetings thus far--27 organizations have been represented at these meetings. Additionally, the team has visited several universities to gain particular insights into potential innovations.

Key Players include companies, universities and National Laboratories interested in all parts of the Tools for Engineered Surfaces food chain, including OEM's, tool manufacturers, coating houses, and component manufacturers. It is expected that, since tool expertise does not reside in any one location, that all projects will include research with all levels. There are quite a few small companies involved in these areas, as indicated by the data in Table VI, and many of these small companies should be in a position to lead or participate in joint venture activities. The following is a sampling of organizations with an interest in this area, most of whom have given us input:

Tool Manufacturers: Praxair Surface Technologies, Miller, TAFA, Sulzer-Metco, Balzers, Engelhard

Universities: UCLA, University of Minnesota, Northwestern University, SUNY/Buffalo, SUNY/Stony Brook, University of Connecticut / Storrs, University of Illinois at Urbana-Champaign, Boston University

OEM's: United Technologies, General Electric, Westinghouse, Dow Chemical, Dow Corning, Caterpillar, John Deere, DuPont, Ford, General Motors

Component Suppliers: AlliedSignal, Timken, DuPont Lanxide Composites, Saint Gobain/Norton

Coating Houses: St. Louis Metallizing, Synterials, Advanced Refractory Technologies, Kennametal, Multi-Arc, Materials Modification

Table VI. Number of Companies of a Particular Size for a Representative Set of Markets in which Engineered Surfaces are Critical

	# of Employees per Establishment			
	<500	**500-999**	**1000-2499**	**>2500**
Mining Machinery	292	3		
Construction Machinery	917	17	5	5

Oil and Gas Machinery	530	2	4	
Aircraft	150	12	11	19
Aircraft Engines and Parts	502	21	11	8
Aircraft Parts and Equipment	1079	19	11	10
Turbines and Turbine Generator Sets	67	6	4	2
IC Engines	263	19	8	4
Farm Machinery and Equipment	1612	13	4	2
Fluid Power	345	2	1	
Fluid Power Pumps and Meters	160			
Industrial Machinery	22755	1		
Bearings	164	16	3	
Motor Vehicle and Car Bodies	388	6	25	37
Motor Vehicle Parts and Accessories	3090	91	43	22

Source*: DOC Bureau of Census, 1992 Census of Manufactures*

Opportunity for ATP Funding to Make a Difference Now

There is a large opportunity for ATP funding to make a difference. Today's industry is locked into near term point solutions which are largely derived through empiricism. Industry does recognize this, but is unable to obtain the resources necessary to change this approach. ATP can offer the opportunity to stretch toward promising new tools on a scale which would otherwise not be pursued. These new tools would not be developed without ATP for several reasons:

1. they are extremely risky and overly integrative;
2. this program would be early in the development of this new brand of technology;
3. the expertise necessary to develop these tools does not exist in any one institution (i.e. OEM's must combine their knowledge of the environmental requirements with the coating manufacturer's feel for the coating process and the tool manufacturer's understanding of how to represent the information from others.);
4. companies of all sizes can successfully obtain internal R&D funds to develop new materials for specific, near-term applications, but not for the tools which would help them develop newer or better materials in later generations.

This ATP focused program is extremely timely. While individual companies would continue to develop point solutions without the help of ATP, Europe and other countries are moving to a more structured approach. Evidence of the level of foreign activity in the engineered surfaces field is illustrated by Table VII which reflects both innovative basic research (as demonstrated by the number of presentations at conferences) as well as commitment to commercialization (as demonstrated by the applications for US patents).

Table VII. Demonstration of world distribution of Engineered Surface Technology through the issuance of U.S. Patents, and Presentations at the largest Applied and Basic Research Meetings

	Surface/Coating U.S. Patents, 1991-1998	ASM International Materials Solution Conference, October 1998, Chicago, IL (applied research)	International Conference on Metallurgical Coatings and Thin Films, April 1998, San Diego, CA (basic research)
Total	334	230	538
% Large Companies	41	11	7
% Medium/Small Companies	19	22	7
% University and Non-profit	6	24	12
% Government	2	15	6
% Foreign	24	27	68
% Private	7	-	-

Technical and Business Scope with Inclusions and Exclusions

Included in the scope of this program will be projects that target the creation of a set of tools which are applicable to materials which provide wear, corrosion and thermal enhancements to substrates and which directly lead to prime reliance for at least one material/application combination. These tools will fall into at least one of the following categories:

- Process diagnostics (including in-line process control and non-destructive evaluation)
- Life / performance prediction (including innovative modeling and simulation)
- Equipment design and development

All projects in this program will address the development and validation of a high risk innovative tool which is potentially applicable to more than one material and application.

Exclusions

- Tools meant specifically for the application of paint
- Tools related specifically to heat treating
- Tools meant specifically for microelectronics
- New materials and processes for their own sake

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