COLD SPRAY TECHNOLOGY:

INTERNATIONAL STATUS

AND USA EFFORTS

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I. INTRODUCTION

Thermal Spray technology is used extensively in defense, aerospace and gas turbine industries. Typical applications include fabrication of components, preparation of protective surfaces, refurbishment of mis-machined and service-damaged parts, etc[1]. Recently, a new Thermal Spray process, known as Cold Spray process, has been introduced to produce metal, alloy, and composite coatings with superior qualities[2]. Cold Spray process uses high velocity rather than high temperature to produce coatings, and thereby avoid/minimize many deleterious high temperature reactions, which are characteristics of typical Thermal Sprayed coatings. Typical advantages of Cold Spray coatings include compressive rather than tensile stresses, wrought-like microstructure, near theoretical density, oxides and other inclusions-free coatings, etc. Moreover, the footprint of the cold spray beam is very narrow yielding a high-density particle beam, which results in high growth rate of coating thickness with better control over the shape of the coating, without masking requirements[2-5]. These advantages can be gainfully exploited for producing engineered bulk forms and coatings for many strategic and other high tech applications.

Cold Spray is a relatively young process and still considerable R&D efforts are needed to both understand and control the process, as well as develop engineered coatings with desired properties for specific applications. The last few years have seen exponential growth of cold spray R&D around the globe[3]. Considerable R&D efforts are being undertaken at various laboratories, academic institutions, and industries. These studies include process diagnostics and modeling of the process and the jet, modeling of the coating formation, spray optimization and application coating development. Europe, in particular, Germany is leading the technology development and applications. As of now in the USA, cold spray technology has been more private industry driven than government funded. A consortium of companies including Alcoa, ASB Industries, Ford, K-Tech, Pratt & Whitney, Siemens Westinghouse had funded Sandia National Lab to execute a CRADA on cold spray technology[4]. Sandia and Penn State University have taken up small developmental activities with funds available from private companies such as Alcoa, Ford and P&W. ASB Industries have teamed up with NASA GRC, Pratt & Whitney and many aerospace industries to develop application coatings for aerospace and gas turbine industries. Though many governments have initiated multi-million dollar programs in their respective countries, government funding in this country has been restricted to small programs funded by Navy[5] and NSF[6].

II. COLD SPRAY PROCESS

The basic **principle** of cold spray is simple (Fig. 1). When a particle-laden gas jet impinges on a solid surface, three different phenomena occur, depending on the particle velocity (V_p). When V_p is low, the particles simply reflect (bounce) off the surface. When V_p reaches moderate values, solid particle erosion of the surface occurs. When V_p exceeds a critical value (which varies with particle and substrate materials – typically in the range of 500-900 m/s), particles plastically deform and adhere to the substrate/one another to form an overlay deposit, analogous to thermal spray coatings. Russian scientists, carrying out supersonic wind tunnel tests, first observed this phenomenon [2]. They developed it into a high deposition spray coating process in the mid-1980s and successfully deposited a wide variety of materials including metals, alloys and composites. Now, cold spray process has been accepted as a new and novel thermal spray technique in the US and other countries.

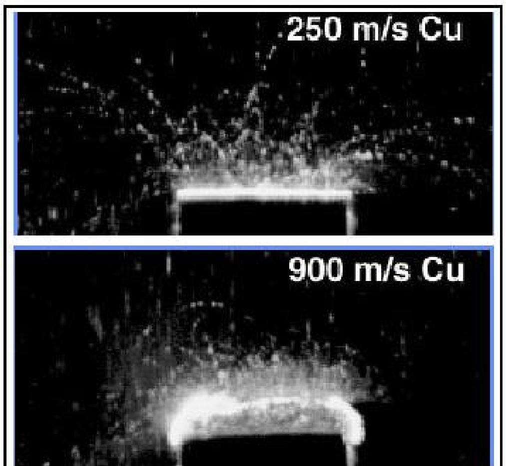

Fig. 1: Cold Spray Principle

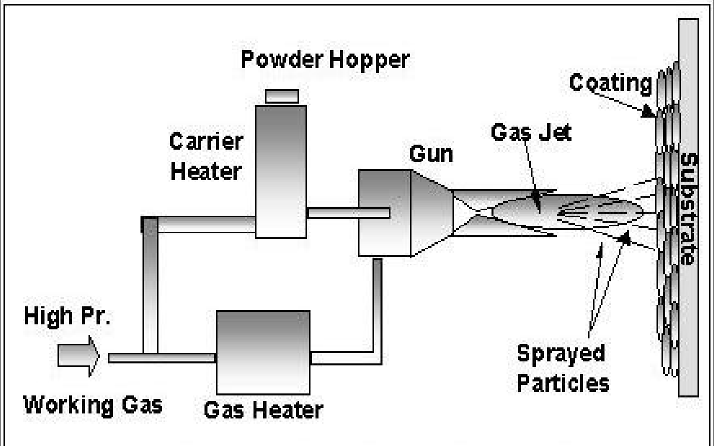

Figure 2: Schematic of Cold Spray Process

Cold spray **process** uses a high pressure, high velocity gas jet to impart the velocity for the coating particles. A high-pressure jet, preheated to compensate for the adiabatic cooling due to expansion, is expanded through a converging/diverging nozzle to form a supersonic gas jet. Powder particles, transported by a carrier gas, are injected into this gas jet. Momentum transfer from the supersonic gas jet to the particles results in high velocity particle jet. These powder particles, on impact onto the substrate surface, plastically deform and form interlinking splats, resulting in a coating.

Figure 3: Cold Spray Systems at ASB Industries, Inc.

A schematic of the cold spray **system** is given in Figure 2 and typical cold spray systems are shown in Figure 3. Typical cold spray system consists of a high-pressure gas delivery system, gas heater, powder hopper, control console and cold spray gun. The gas delivery system supplies up to 170 m^3/Hr (100 SCFM) of nitrogen and/or helium at the pressure levels of 15-40 bars (215-580 psi). An electric gas heater heats the gas to a maximum of 923 K (1200° F). Powdered coating material, in the size range of 5-45 microns, is delivered by the powder hopper and transported by a carrier gas to the gun. The control console houses all the controls to meter the gas flow rates, pressures, powder feed rate, etc. Conventional job handling systems are used to scan the spray beam over the substrate surface.

Cold spray is a solid state process and hence produces coatings with many advantageous characteristics. Since high temperature is not involved, it is ideally suitable for spray depositing temperature-sensitive materials such as nanophase and amorphous materials, oxygen-sensitive materials like aluminum, copper and titanium and phase-sensitive materials such as carbide composites. Due to small size of the nozzle (10-15 mm^2) and spray distance (5-25 mm), the spray beam is very small, typically around 5 mm diameter, which translate into precise control over the area of deposition over the substrate surface. Cold spray process works similar to a micro shot peening devise and hence the coatings are produced with compressive stresses. Thus, ultra thick (5-50 mm) coatings can be produced without adhesion failure. The high energy-low temperature formation of coating leads to a wrought-like microstructure with near theoretical density values.

III. COLD SPRAYED COATINGS AND FREEFORMS

Cold spray process has been used to produce dense, pure, thick and well bonded coatings of many metals (Al, Cu, Ni, Ti, Ag, Zn,), alloys (SS, Inconels, Hastalloys, MCrAlYs) and composites (metal-metal like Cu-W, metal-carbides like Al-SiC, metal-oxides like Al-Alumina) and others. Figure 4 gives the microstructure of a few cold spray coatings. As can be seen, near theoretical density could be obtained in the as-sprayed condition, with proper optimization of spray parameters.

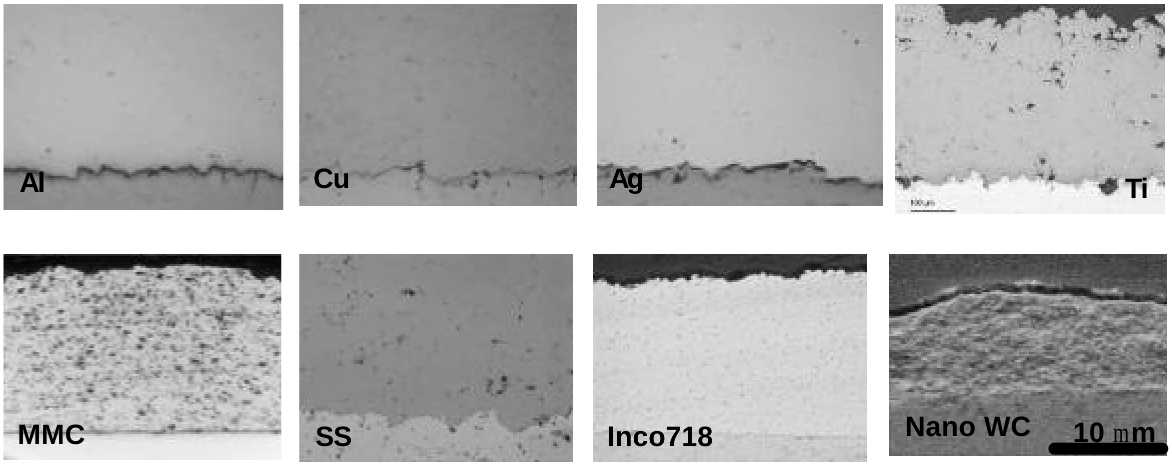

Figure 4: Microstructures of Cold Sprayed Coatings

Cold spray has been used to produce protective coatings and performance enhancing layers, ultrathick coatings, freeforms and near net shapes[3]. Figure 5 and 6 show some of the coatings and bulk forms produced by cold spray process at ASB Industries. Large size and shapes can be spray fabricated and geometrical features can be easily incorporated during spray preparation and machine finished. Since the cold spray gun is frequently handled by a robot, CAD files can be used to control the spray pattern to produce near net shapes (NNS). Moreover, by controlling the feedstock composition, one could vary the deposit microstructure and composition to produce functionally gradient materials (FGM) and other special structures.

Typical protective coatings include MCrAlY coatings for high temperature protection and bond coats for thermal barriers, copper-chrome layers for oxidation protection of GRCop-84 structures, corrosion resistant aluminum and zinc coatings for oil and auto industries and others. ASB has carried out extensive work on development of cold spray process for thick coatings/freeform fabrication. In aerospace industry alone, ASB also has produced many applications, most of which are proprietary. Some of the open applications include (i) Cold sprayed Thermal Management Layers for RL60 rocket engine[7], (ii) Copper – Carbon MMC Thermal Management Layers for NASA GRC and (iii) Cold spray fabrication of slabs and plates of high strength copper alloys.

Unfortunately, most of the data on properties of cold sprayed coatings are proprietary in nature and is not available on open literature. However, some results have been published and have been compiled in Table-I. Analysis of these results shows the following.

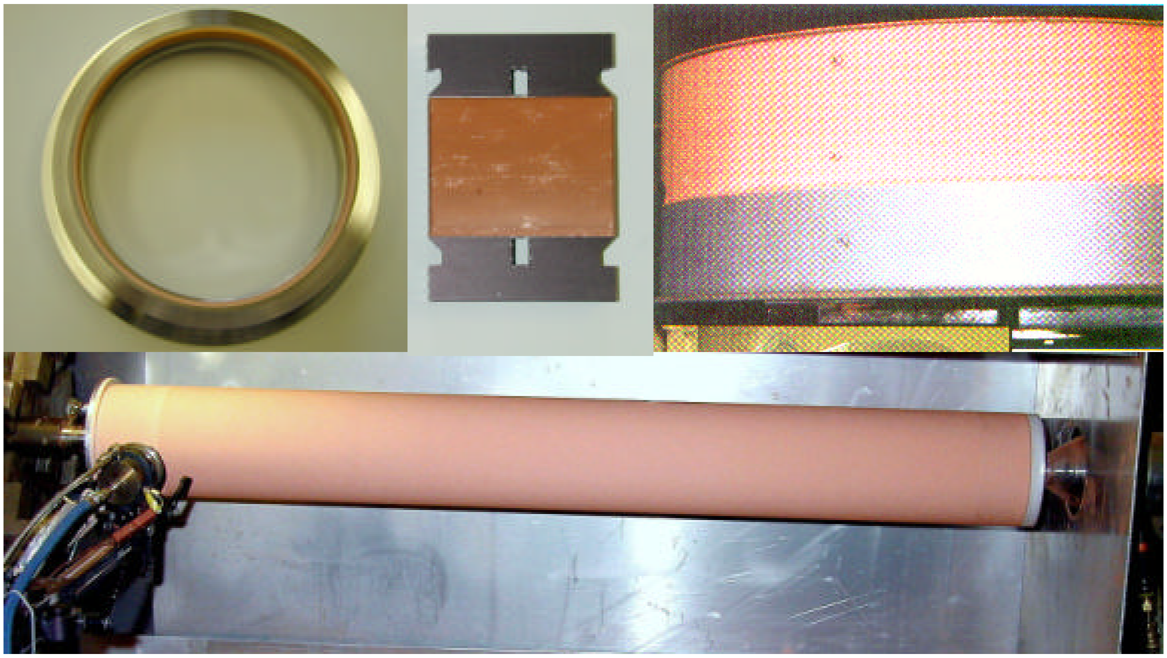

Figure 5: Typical Cold Sprayed Coatings

Figure. 6: Cold Spray Produced Bulk Forms

TABLE - I					
MATERIAL PROPERTIES					
Material	**Condition**	**Young's Modulus (GPa)**	**Yield Strength (Mpa)**	**Ultimate Strength (Mpa)**	**Strain (%)**
Nickel	Bulk	207	59	317	0.3
	As-Sprayed	158	300	300	0.0002
	Heat Treated	125	207	304	0.0956
Copper	Bulk	110	220		
	As-Sprayed	103	266		
	Heat Treated	104	195		
6061 Aluminum	Bulk	65.5	83	152	18
	As-Sprayed		241	241	0
	Heat Treated	51	91	157	18
Hastalloy C	Bulk	30			
	As-Sprayed	142			
	Heat Treated				
CoNiCrAlY	Bulk	41			
	As-Sprayed	98			
	Heat Treated				

1. cold spray produces coatings and freeforms with required density, strength and other characteristics.
2. Cold sprayed coatings have near zero ductility in the as sprayed condition, and post spray heat treatment is required to retrieve the ductility.
3. Full strengthening mechanism of the dispersion strengthening process is not achieved in cold sprayed MMCs. It is believed that the fracturing of the dispersant particles during the spray process results in this reduction in coating strength.
4. Strength and modulus values of the sprayed coatings reach those of wrought material only in some cases such as 6061 aluminum alloys.
5. R&D efforts could result in enhancing the characteristics of other materials such as Inconels.

IV. ECONOMICS OF COLD SPRAY PROCESS

Apart from the technological advances, the other main goals of any process improvement are large reductions in cost and lead-time. To achieve these reductions, it is necessary to address all aspects of manufacturing involved in the fabrication of specific components. Most engineering structures are typically cast, and Figure 7 shows the costs involved in all the different processing operation of a typical cast part. This analysis, termed as value stream analysis[8], clearly shows that a huge reduction in cost cannot be achieved through a reduction in one area only. The Value Stream model was developed by Pratt & Whitney as part of the USAF Forging Supplier Initiative (FSI) for Laser Powder Deposition (LDP) of titanium [8]. Also under FSI, this LPD cost model was extended to model the cold spray process for titanium.

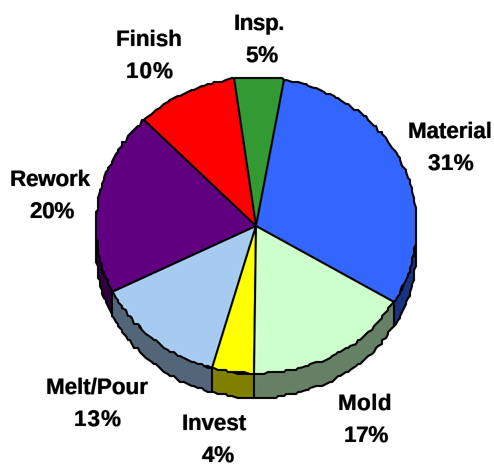

Figure 7: Value Stream Analysis of Casting

The cold spray titanium cost model was exercised to predict the "should" cost of making deposits of various complexities. Sensitivity of these "should" costs to input variables such as powder cost, utility and shop rates, deposition precision, etc., was also carried out. This study showed that manufacturing using the cold spray process attacks many aspects of the value simultaneously. Judged against the value stream results, use of this technique accomplished (i) reduction in material input, (ii) elimination of mold and melt pour cost, (iii) reduction in rework, (iv) reduction in finishing and (v) large increase in material utilization (cold spray has deposition efficiency of 60-95%). A simple calculation, based on the value stream results showed that if raw material input can be reduced by 50%, rework and finishing by 75%, and mold, melt/pour, and casting costs removed, 70% of the value stream would be eliminated. Of course, this needs to be balanced by the added cost of directly fabricating the component using cold spray. These estimated deposition costs were then used to help develop business cases to ***show that a cost advantage could be obtained by fabricating parts using the cold spray process.***

V. COMMERICAL POTENTIAL OF COLD SPRAY PROCESS

Commercialization opportunities of well developed cold spray technology exist in both general cold spray technology and high performance freeforms. Matured cold spray technology can be used to produce both protective coatings and prototyping/freeform fabrication in not only strategic industries such as defense and aerospace, but also in various other general industries such as steel, utilities, paper and pulp, etc. High performance materials such as superalloys, MMCs and nanostructured materials are used to produce complex and intricate components of various high tech industries. Established cold spray process can cater to economical and fast prototyping and fabrication of these components.

Cold sprayed 'production coatings' have already been supplied to a few industrial customers. Moreover, many R&D programs for developing engineered coatings for specific industrial applications are being pursued by ASB and others. For instance, aluminum and aluminum alloy coatings are being investigated for repair/refurbishment of space shuttle solid rocket boosters and others (aerospace), repair and retrieval of parts and plate stocks used in aircraft structures (aircraft industry), repair/refurbishment of casings (gas turbine), corrosion protection coatings (petrochemicals), brazing/joining (utility) and others. Similar to aluminum, studies are being pursued with copper (steel, electronics, aerospace), titanium and tantalum (electronics, bioengineering), etc. Matured technology will establish cold spray as a viable technique for producing high performance coatings reproducibly at affordable cost, and result in commercial exploitation of the above and many other applications.

Successful application of cold spray process in one (say aerospace) industry will induce commercial applications in other high technology industries, such as nuclear, biotechnology, etc. At present, high performance layers such as high temperature oxidation resistant MCrAlY coatings, high conductivity copper/silver coatings, phase-pure biocoatings, etc., are produced in Vacuum Plasma Spray systems or Physical Vapor Deposition systems. These systems are extremely expensive to both install and operate. Cold spray process can produce coatings with comparable microstructure and properties, **in open atmosphere**. Moreover, cold spray process may lend itself to collect the overspray and reprocess these expensive raw materials. Hence, well founded cold spray technology will be able to compete for a good market share of VPS/PVD coatings in turbine, power, electronic/electrical, biotechnology and other industries. Similarly, cold spray can produce MMC coatings and freeforms with any dissimilar materials, even with graded properties and hence can achieve a share of the MMC market as well.

VI. INTERNATIONAL STATUS

Cold spray process can yield good quality coatings and freeforms of many engineering materials. However, further R&D efforts are required for achieving acceptable coatings with desired characteristics. As noted earlier, many governments have initiated research programs in their respective countries. In many countries, multiple organizations are involved in different aspects of the technology.

A conference on cold spray technology, Cold spray 2002, held in Albuquerque in 2002 attracted around 75 participants, including about 15 from abroad[9]. In 2004, the same conference (Cold spray 2004) was attended by 151 participants from 14 countries, showing the growth of cold spray interest around the globe[10].

Surveying the published literature and discussions with various scientists have shown the details given below.

Australia: Council of Scientific and Industrial Research Organization (CSIRO) – Manufacturing and Infrastructure Technology Division in Melbourne has been entrusted with cold spray technology development for industrial applications. Dr. Mahnaz Jahedi is the technical leader of the group established in 2003 with a German built CGT Kinetic 3000 system[11].

Belgium: Recently a CGT system has been installed in a thermal spray job shop in Belgium[12].

Brazil: Initially, they purchased the license from the inventor of cold spray process, and he helped them assemble an in-house built system to carry out studies on applications in repair, refurbishment and protection of mining equipments and parts. Much information is not available on their experiments. However, encouraged by the results, they have now purchased a CGT system form Germany[12].

Canada: Dr. Christian Moreau of National Research Council (NRC), Canada has ***received a multi-million dollar grant*** to incorporate cold spray technology into his already well-established thermal spray facility[13]. He is in the process of building the cold spray facility with multiple cold spray systems. He plans to carry out diagnostic studies (he is a world leader in thermal spray process diagnostics) and also form industrial collaborative teams to develop aerospace applications.

Prof. Roman Maev of University of Windsor, Canada, has developed his own low-cost cold spray system, suitable for producing MMC coatings[14]. Apart from government funding, Daimler Chrysler Corporation as well contributes to his research activities to develop corrosion protection layers for automotive applications. These developments have led to commercialization of the system through a private company called Centerline[15].

France: Two organizations (Atomic Energy Commission and School of Mines, Paris) have received funds to pursue cold spray research. Moreover, a Job shop as well has installed a CGT system to cater to commercial needs[12].

Germany: Germany is the world leader in cold spray technology. Multiple institutions are pursuing cold spray technology research, including Federal Armed Forces University, Hamburg, European Aerospace Research Institute (EADS), Ottoburnn (in collaboration with Aachen University, Aachen), Linde Corporate R&D, Munich and CGT Technologies, Munich.

Prof. Heinrich Kreye of Federal Armed Forces University, Hamburg leads a team of about 10 scientists and engineers including 4 Ph.D.s. His lab is involved in all aspects of cold spray technology, including theory, modeling, design and development of nozzles, preparation and characterization of coatings, development of application coatings, etc[16]. Dr. Vlcek of EADS studied ***cold spray fabrication of aerospace components*** as a part of his Ph.D. thesis[17]. Linde R&D and CGT Technologies are carrying out a large number of application studies to develop engineered coatings for various industries[18].

Germany realized early that the availability of a reliable cold spray system to produce reproducible coating is of paramount importance and that cold spray system development is a multi-disciplinary one. Hence they formed a consortium of Federal Armed Forces University, Hamburg, Linde R&D and CGT Technologies to pool their respective expertise of Materials science, Gas technology and Process control equipment to evolve the Kinetic 3000 cold spray system[19]. Now, over a dozen of these systems have been purchased by various organizations around the globe.

World's first mass production application of cold spray process has been developed in Germany. This application was developed by Prof Kreye and uses the high thermal conductivity of cold sprayed copper to serve as thermal management layers in high performance heat sinks. OBZ Dresel & Grasme GmBH is producing cold sprayed heat sinks for both electronics and automobile industries[20].

Japan: Prof Sakaki of Shinshu University had been pioneering cold spray R&D in Japan. He has carried out both theoretical and experimental studies[21]. Recently, researchers from many other universities and research institutes including Prof Kuroda of National Institute of Materials Science have initiated activities as well. A consortium of academic, research and industrial partners has been formed in 2004 to expedite cold spray R&D[22]. Moreover, a few industries including Toyota and Nippon Steel are negotiating to install multiple cold spray systems for captive applications.

Russia: Cold spray process was developed and patented in the eighties by the scientists working in the Institute of Theoretical and Applied Mechanics at Novasibirsk, Russia[2]. Since then, this group has been active in both theoretical and experimental studies. They have developed the two-dimensional gas dynamic model of the flow, heat and momentum transfer from gas to particles, particle impact and deformation theory, coating microstructural development, etc. they have also carried out extensive spray experiments and developed many application coatings[23].

Induced by the success of the cold spray process around the globe, various groups in Russia have come out with different versions of gas-particle two-phase coating deposition processes. These processes use compressed air, nitrogen and helium as the carrier gas at wide range of gas temperature and pressures to produce some coatings with acceptable characteristics. However, systems based on these processes are relatively cheap. These processes have been marketed with various brand names such as Rus Sonic, Tev Tech, Dymet, etc[24,25].

South Korea: Multiple groups are involved in cold spray R&D, including Dr. Lee of Hanyang University, Dr. Kim of RIST and others. Dr. Lee is working in collaboration with the automobile industry. It is believed that he is in advance stages of commercialization of a few applications[26].

United Kingdom: An automobile parts company, Yazaki, is one of the first in the world to start cold spray R&D. Over the last five years, they have developed copper harnesses for automobile electrical applications.

University of Nottingham has a large cold spray program. They have already produced a Ph.D. on cold spray technology[27].

British Oxygen Corporation is working in collaboration with Cambridge University on the helium recovery and recycle system. They have already designed and built a system in Cambridge cold spray facility. At present, commissioning and testing studies are going on[28].

Prof William O'Neil of Cambridge University has ***received a large grant of about two million dollars*** for cold spray R&D. this grant will be used for cold spray manufacturing of near net shapes and tools[29].

VII. UNITED STATES EFFORTS

Cold spray technology was introduced in USA in early 90s by a CRADA, conducted by the National Center for Manufacturing Studies, Toledo. Dr. Anatoli Papyrin, the patent holder of cold spray process was brought from Russia to build the cold spray system and carry out spray studies[30]. Though Ford, Pratt and Whitney and other industries showed interest in the technology, and one job shop (ASB Industries) purchased the license for commercial exploitation of the technology, the cold spray technology did not grow as expected. As yet, the US government funding for the technology development has not been as good as it is in many other countries such as Germany, United Kingdom, Canada, etc.

Penn State University initiated cold spray R&D when Dr. Papyrin moved there and now they have received small grants from Navy to develop anti skid coatings[5].

A consortium of companies including Alcoa, ASB Industries, Ford, K-Tech, Pratt & Whitney, Siemens Westinghouse had funded (about 0.5 million a year for 3 years) Sandia National Lab to execute a CRADA on cold spray technology[4]. Under this CRADA, P&W patented foul-free nozzle was developed to avoid catastrophic failure of spray operation during the processing of aluminum and many other engineering materials. Sandia has also taken up small developmental activities with funds available from private companies such as Alcoa, Ford and P&W. Ketch Corporation has obtained the license to build and sell cold spray equipment in USA.

ASB Industries has teamed up with NASA GRC, Pratt & Whitney and many aerospace companies to develop application coatings for aerospace and gas turbine industries. ASB also has developed application coatings for general industries such as Alcoa, Exxon Mobil and others. ASB also has carried out R&D on gun and nozzle development. Intellectual properties, arising from these studies have been subject of various patents, obtained and filed[31-34]. Some of the coatings and freeforms, produced by ASB are given in Section III.

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